# Imaging the subsurface electrical resistivity/conductivity from electric and electromagnetic methods

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# Content

- Overview of resistivity
- Case study using Electric and electromagnetic methods
- Time-domain electromagnetic method (TDEM)
- Case study TDEM
- Summary

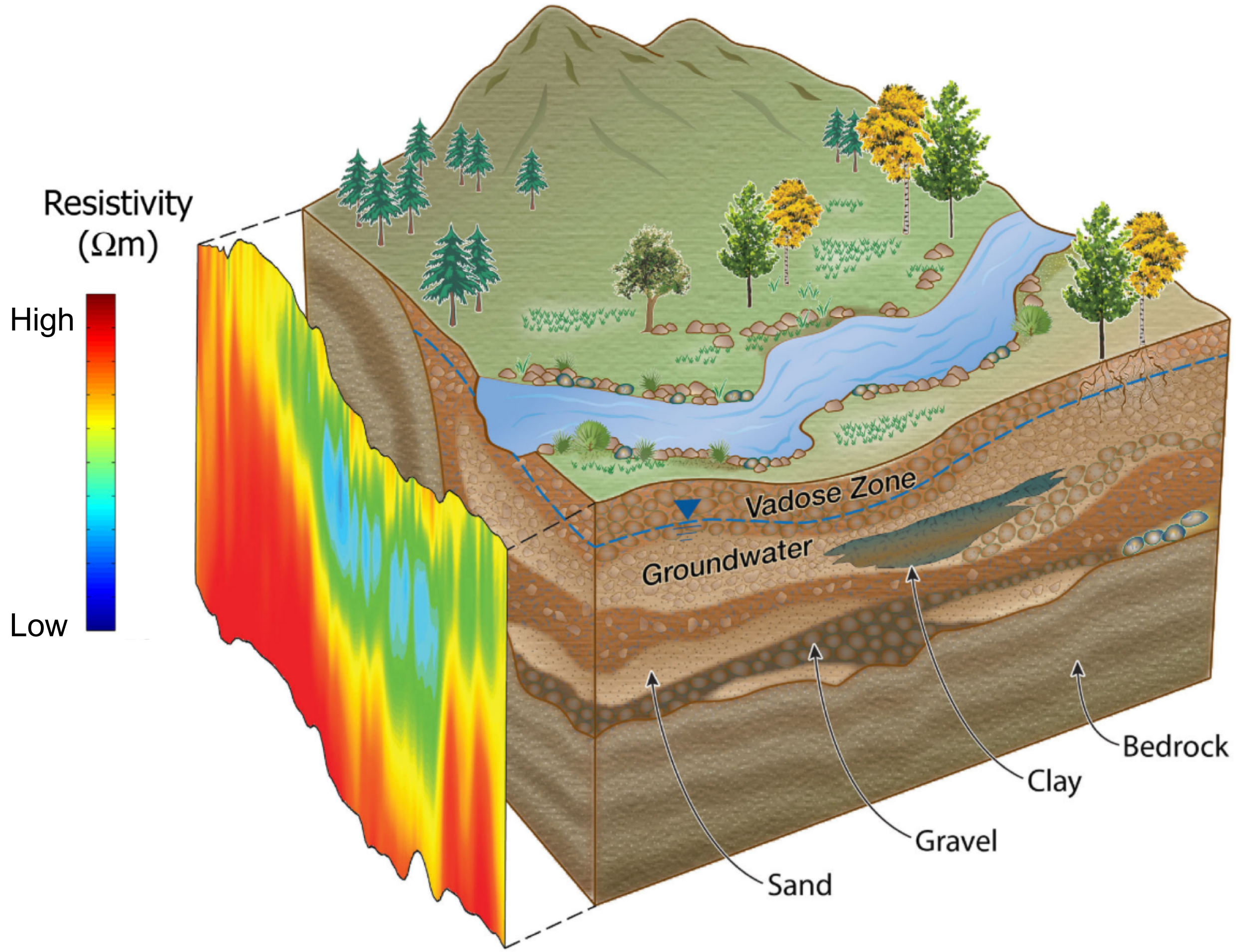
# Electrical resistivity/conductivity

- What is it?
- Why is it important?
- How do we measure it?

# Electrical resistivity/conductivity

- **What is it?**
- Why is it important?
- How do we measure it?

How easy/difficult an electric current flows through a certain material.




Binley et al., Water Resour. Res., 2015

# Resistivity

- What is it?
- Why is it important?
- How do we measure it?

- Geotechnics
- Hydrogeology
- Ice thickness
- Ore deposits
- Tectonic faults
- Geothermic
- Agriculture

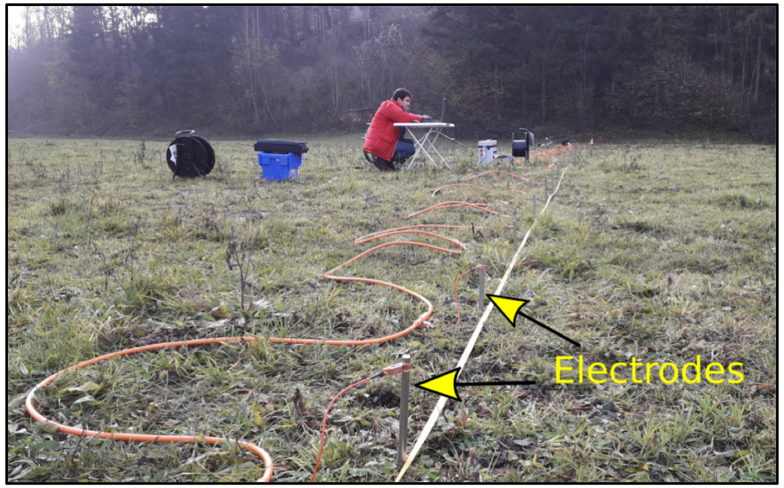
# Electrical resistivity/conductivity

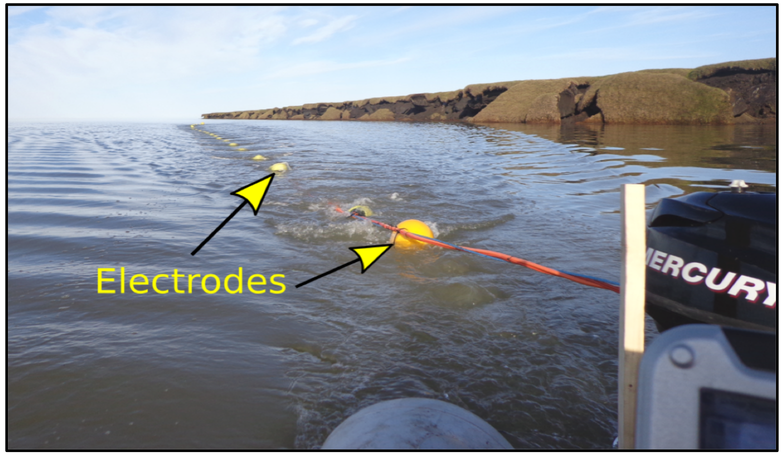
- What is it?
- Why is it important?
- How do we measure it?

- Electrical resistivity tomography (ERT)
- Frequency-domain electromagnetic methods (FDEM)
- Time-domain electromagnetic methods (TDEM)
- Magnetotelluric methods (audio and controlled source)
- …

# Electrical resistivity tomography

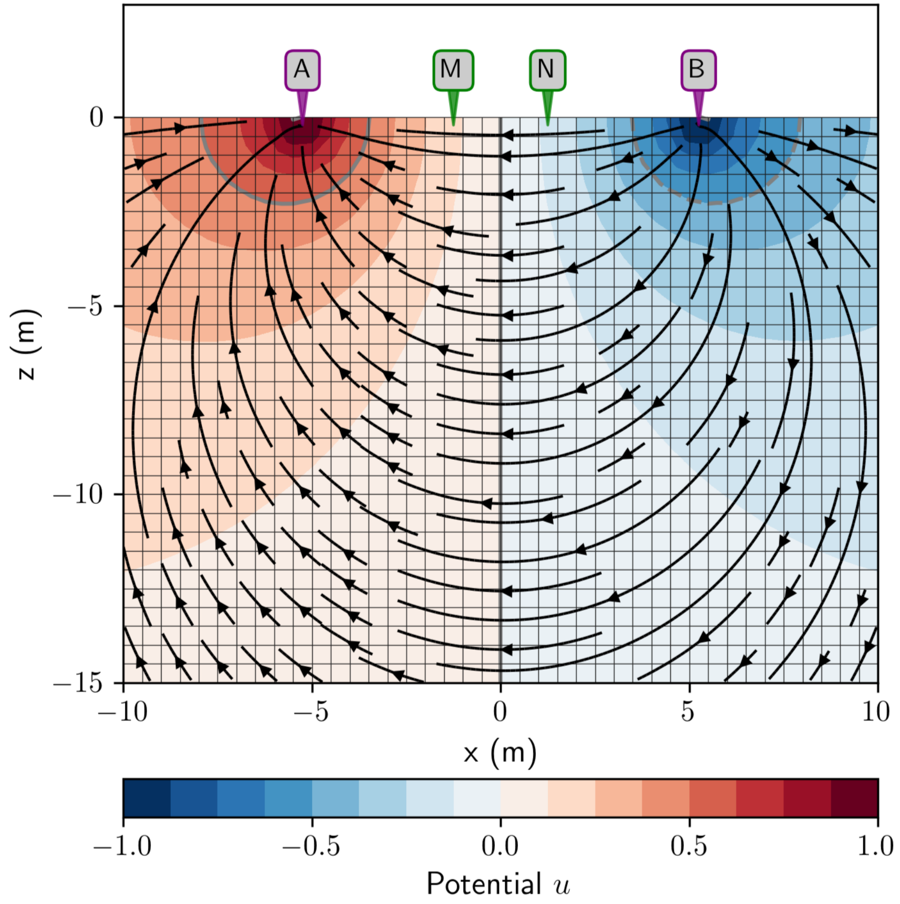
- What is it?
- Why is it important?
- How do we measure it?

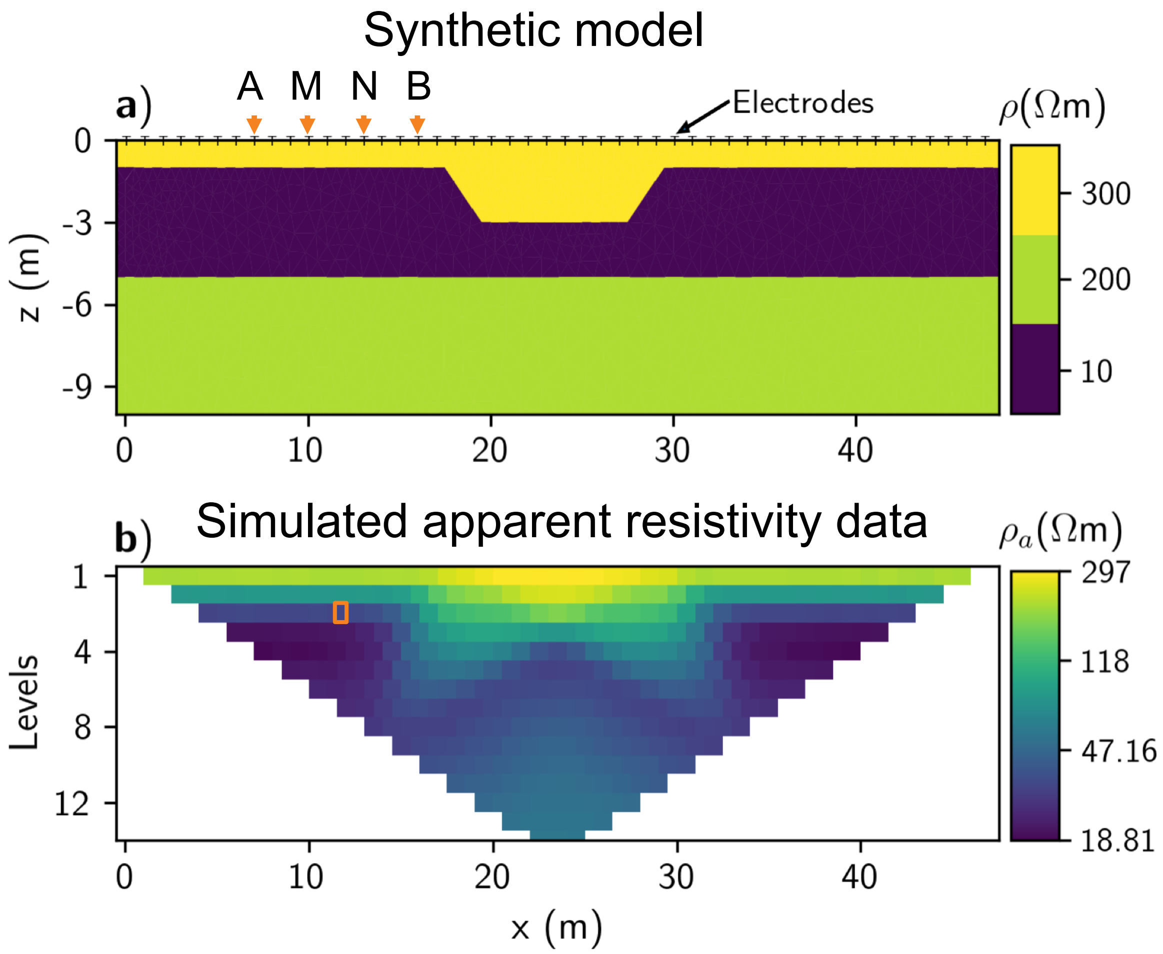



DC resistivity method (e.g., ERT) → Ohm's law

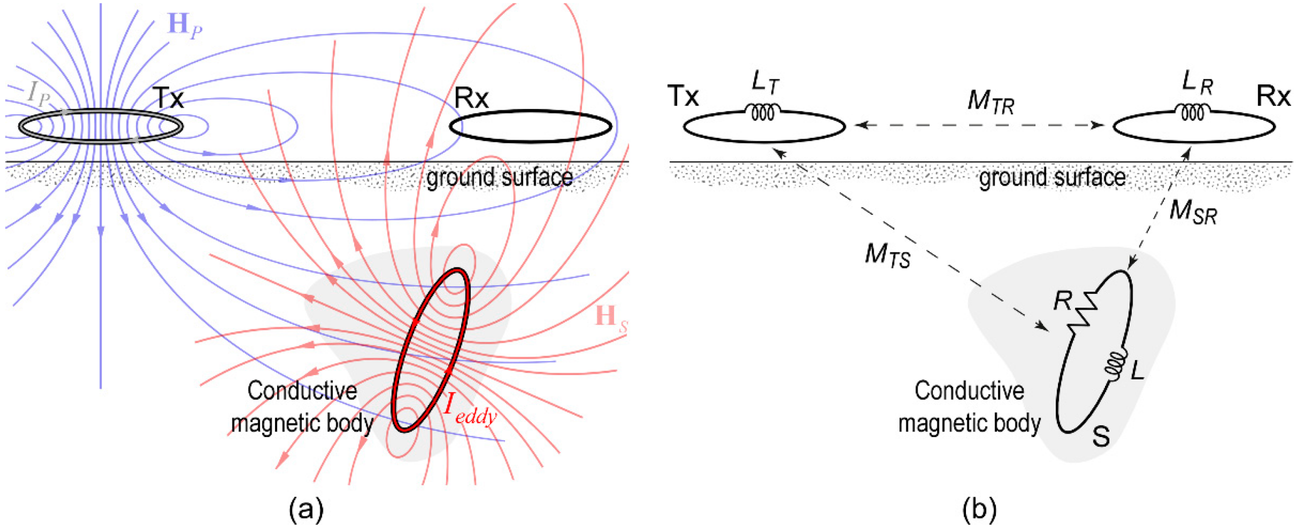
# Electrical resistivity tomography



# Electromagnetic induction

- What is it?
- Why is it important?
- How do we measure it?



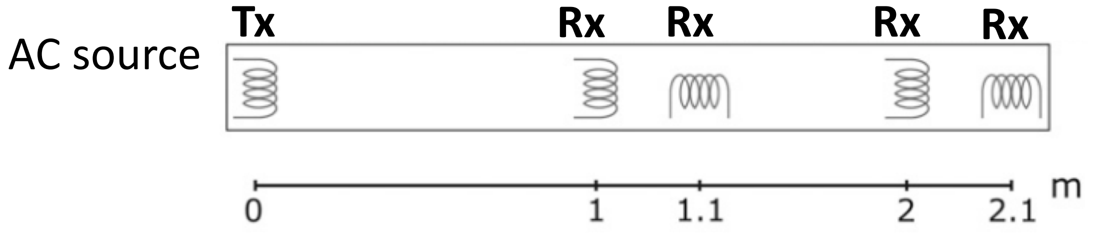

Piero Deidda, et al. (2023), Remote Sensing

**Frequency domain EM**

- Amplitude and phase shift analyses
- Contamination of noise by removing the primary EM field
- Transmitter current is typically a sinusoidal wave

**Time domain EM**

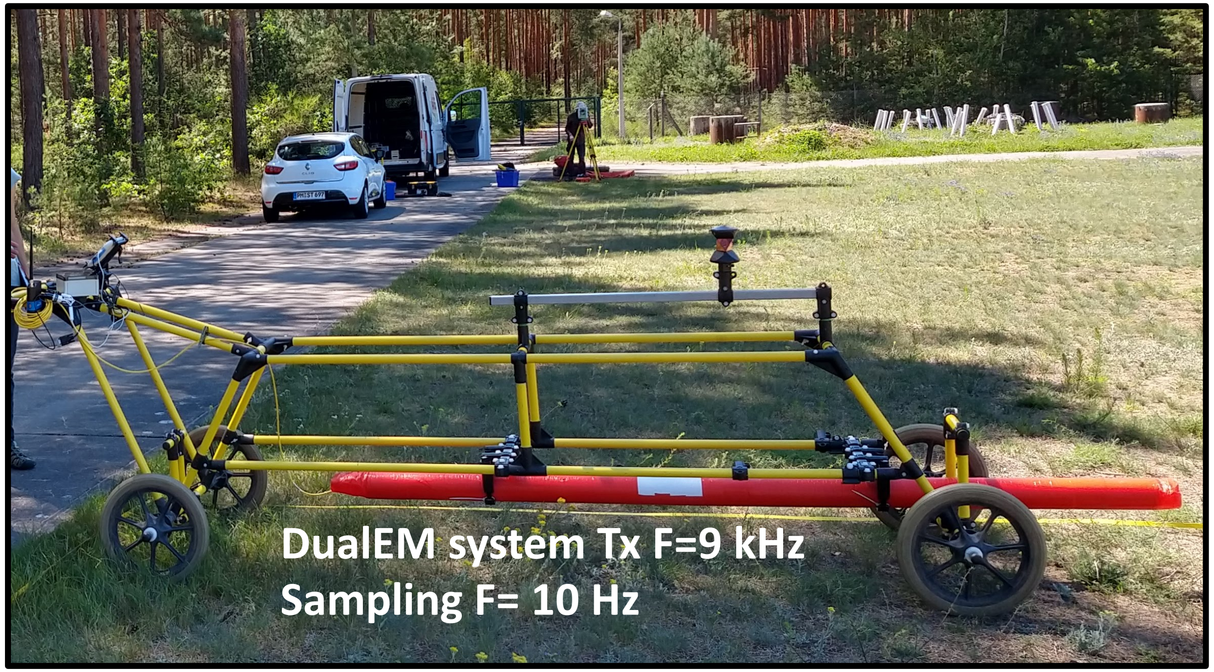
- Transient decay of the secondary field
- Broadband (wide band), which measures data in a wide frequency range
- Sensitive to telluric noise (not a big issue for modern devices)
- Transmitter current is typically a square wave



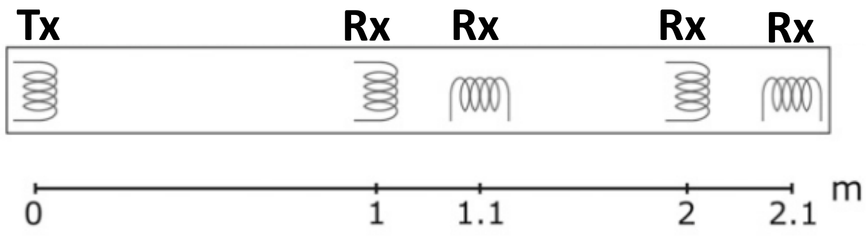

Saey et al. (2009), SSSAJ

# Electromagnetic induction

- What is it?
- Why is it important?
- How do we measure it?




AC source



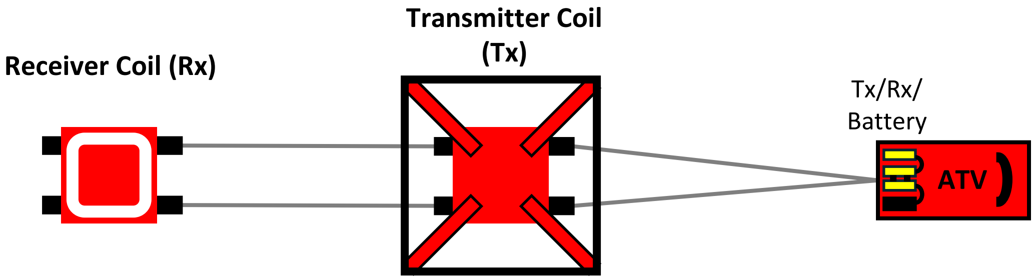

Saey et al. (2009), SSSAJ

Maxwell's equations and constitutive relations (i.e., relations between field and fluxes)

DualEM is **Frequency domain**: amplitude and phase shift (respect to primary) or in-phase (real) and out-of-phase (quadrature) components

# Electromagnetic induction

- What is it?
- Why is it important?
- How do we measure it?



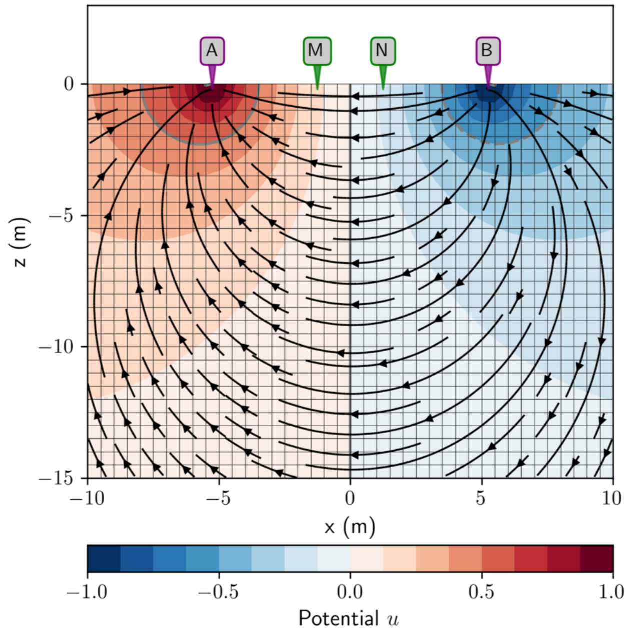


Maxwell's equations and constitutive relations (i.e., relations between field and fluxes)

Towed transient EM (tTEM): Measure the decay of the secondary magnetic field

# Electric vs electromagnetic methods

We can obtain the electric resistivity/conductivity using electric and electromagnetic methods.

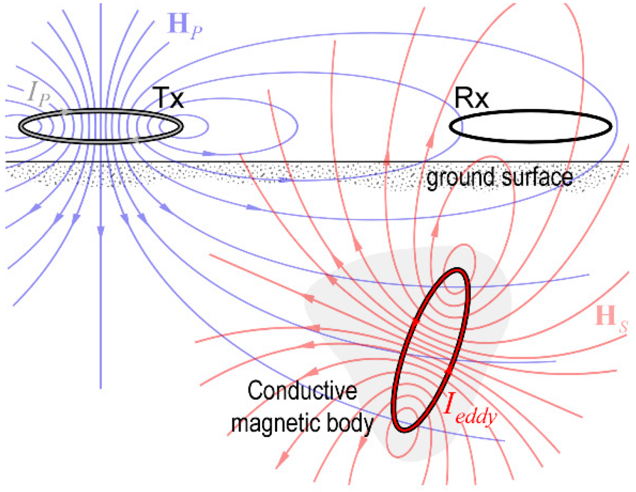



Electric method

- Advantages
- Disadvantages

Electromagnetic method

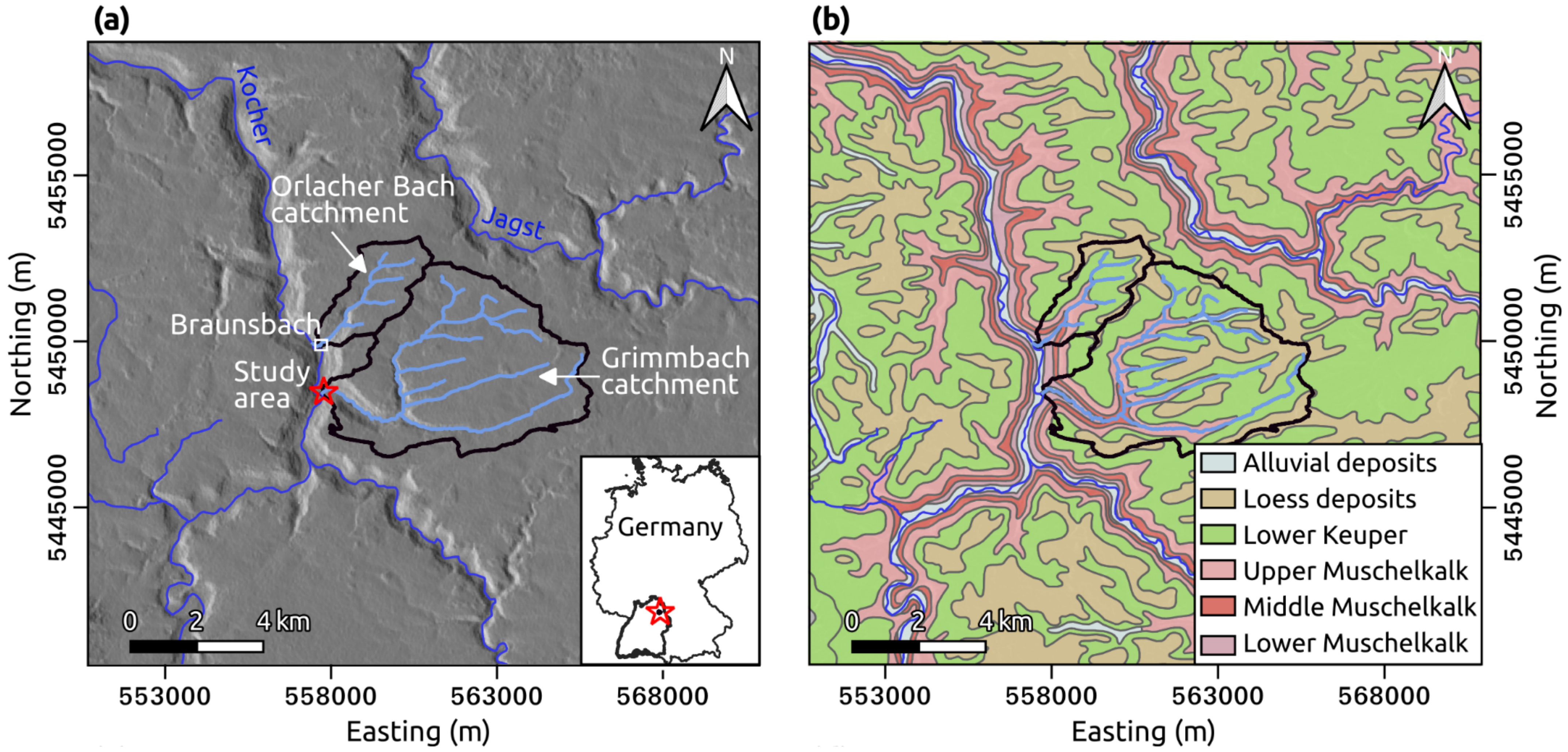
- Advantages
- Disadvantages




(a)

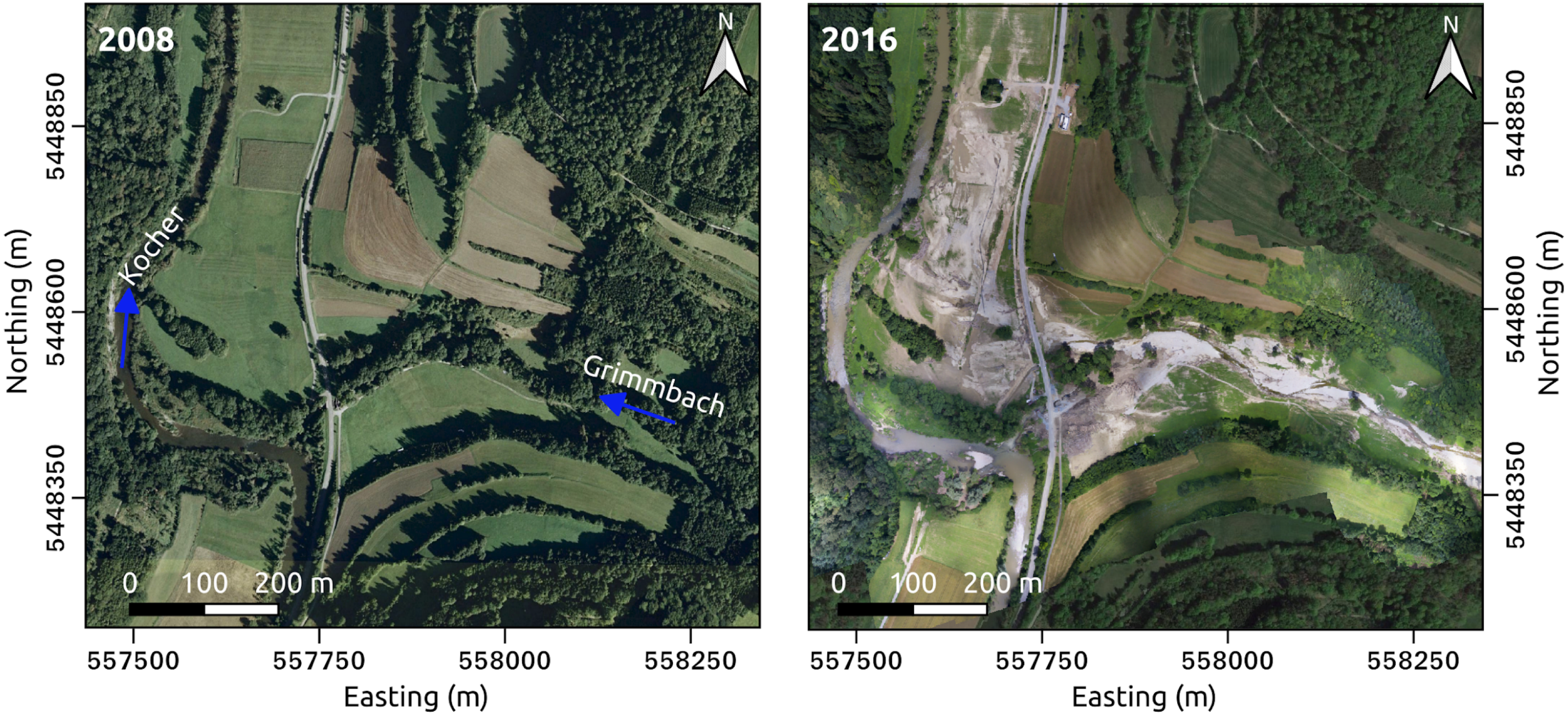
Piero Deidda, et al. (2023), Remote Sensing

# EMI and ERT in practice: Braunsbach




Arboleda-Zapata et.al. (2023), ESPL

# EMI and ERT in practice: Braunsbach

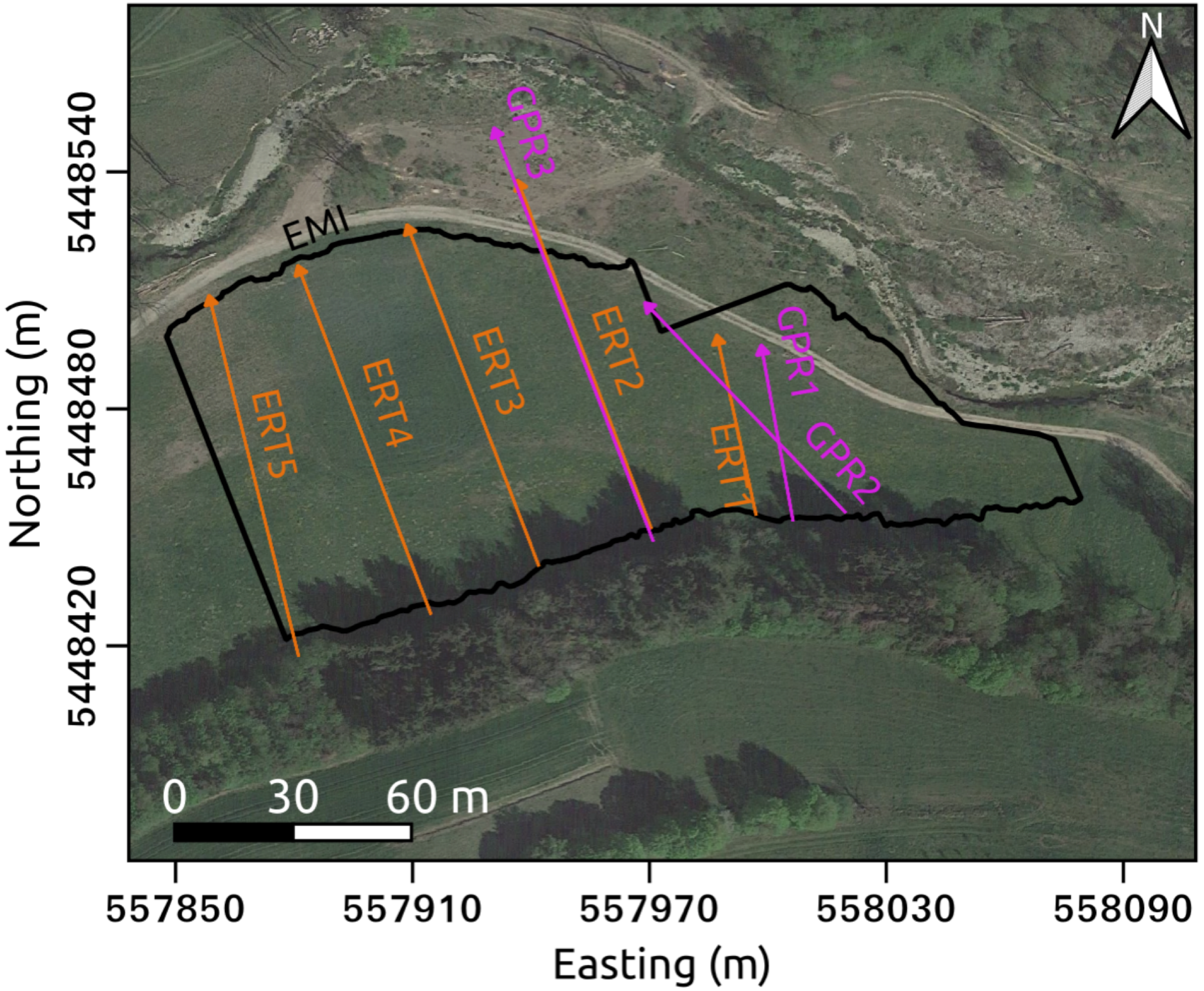


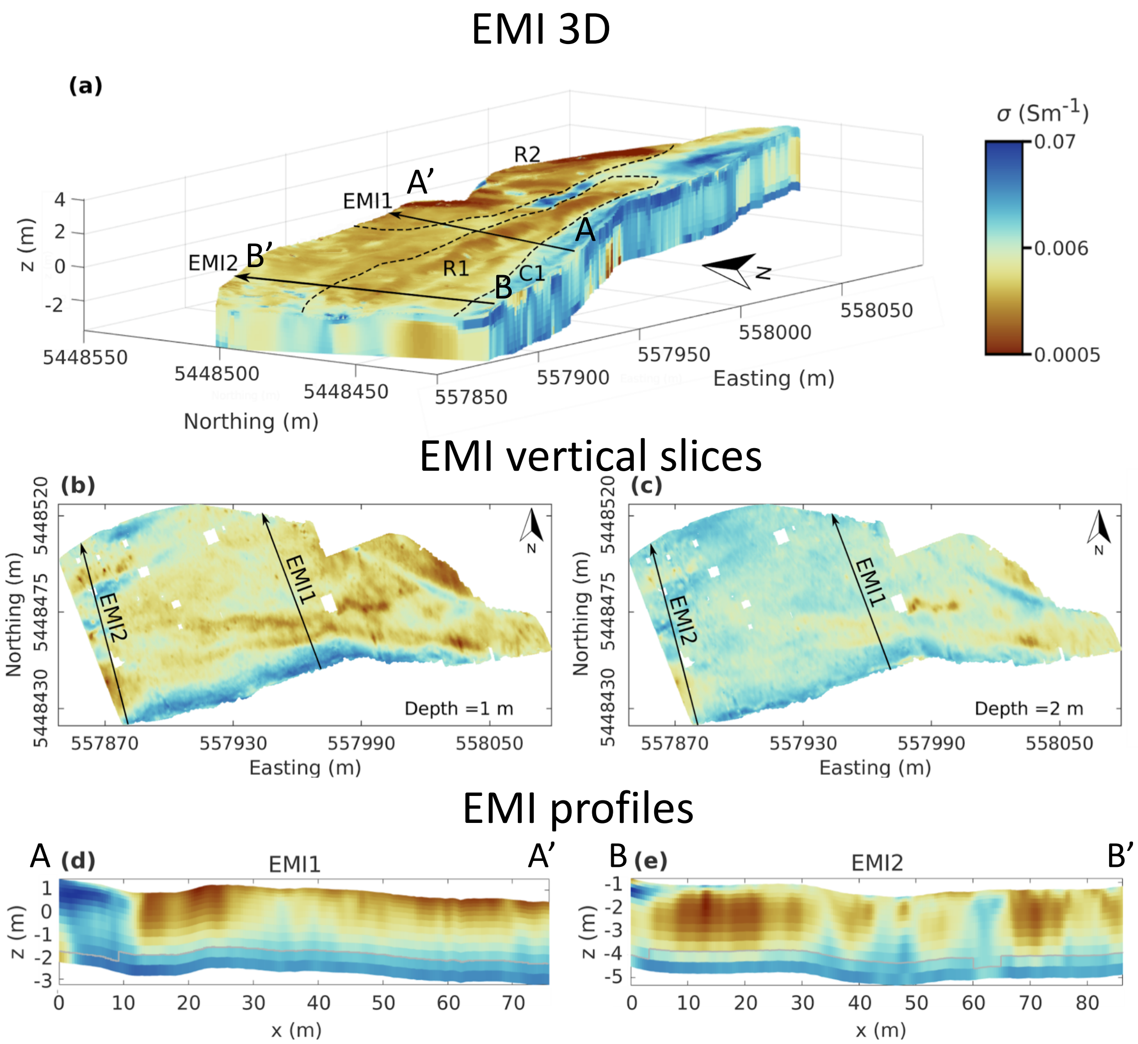

Arboleda-Zapata et.al. (2023), ESPL

# EMI and ERT in practice: Braunsbach

Arboleda-Zapata et.al. (2023), ESPL

# EMI and ERT in practice

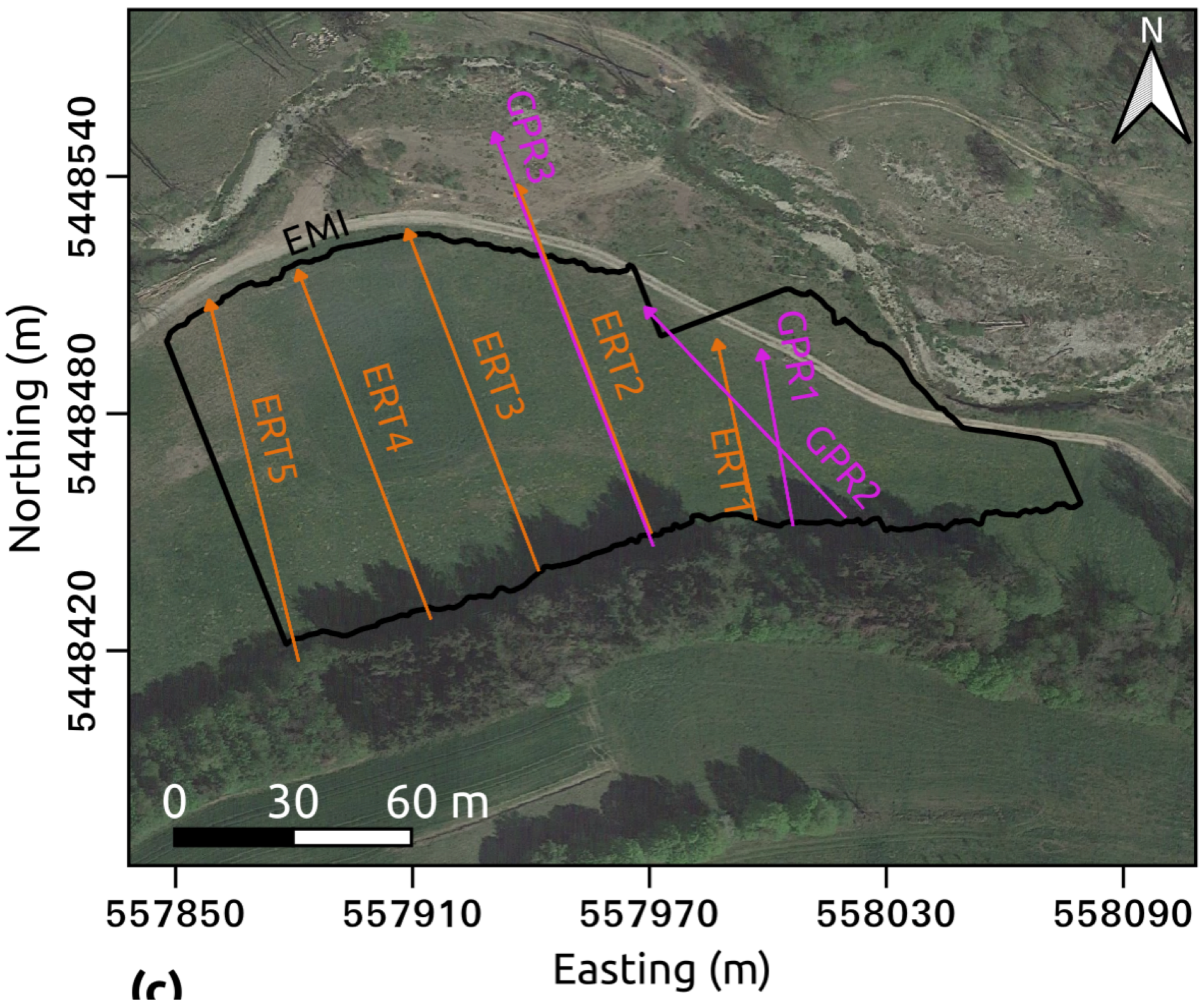


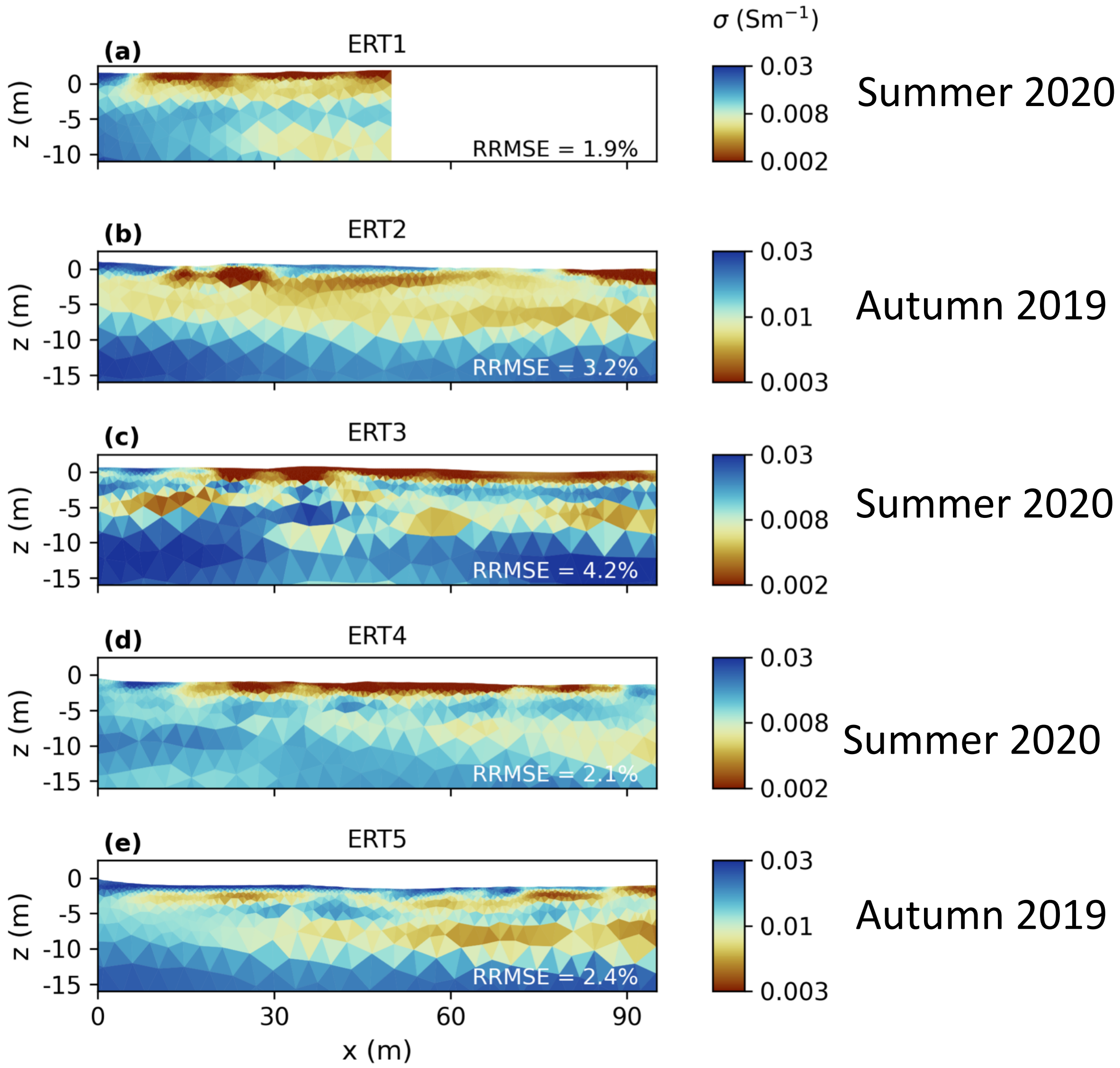




EMI Profiles ~ 0.5 m spacing

Arboleda-Zapata et.al. (2023), ESPL

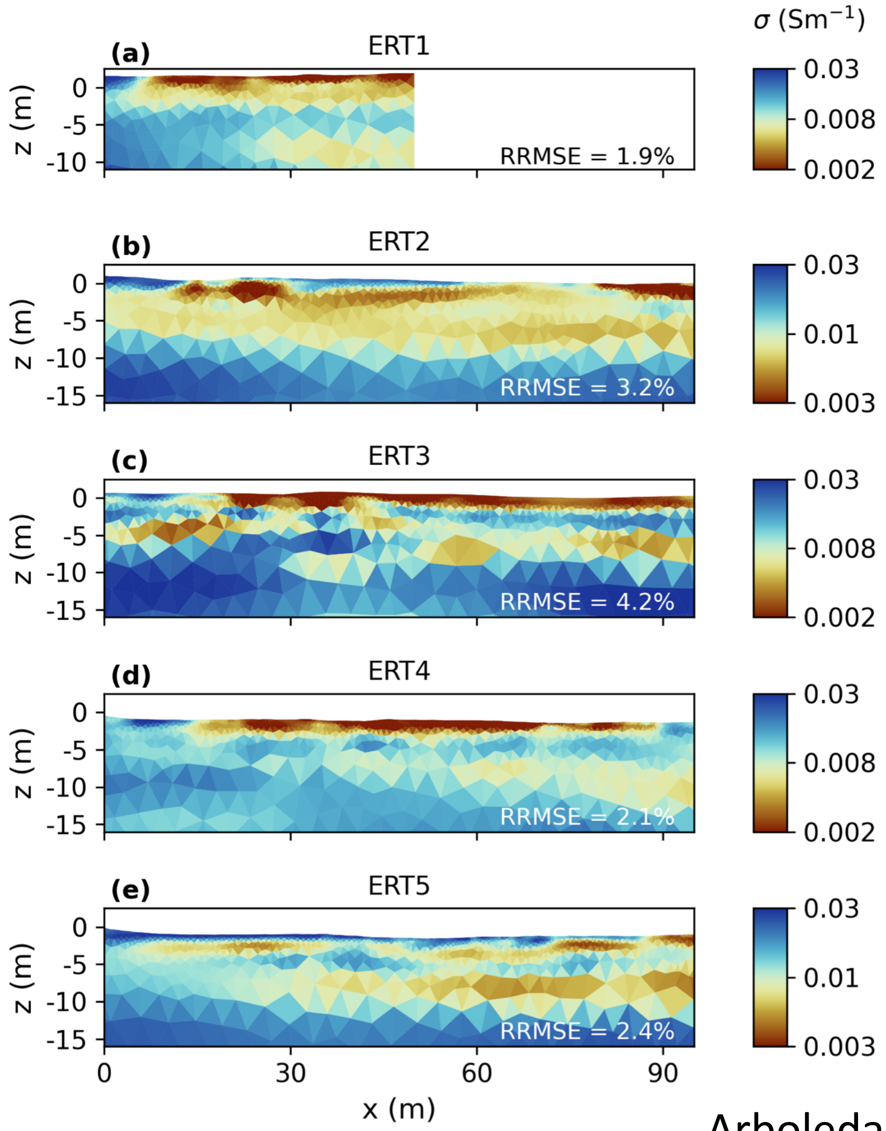
# EMI and ERT in practice

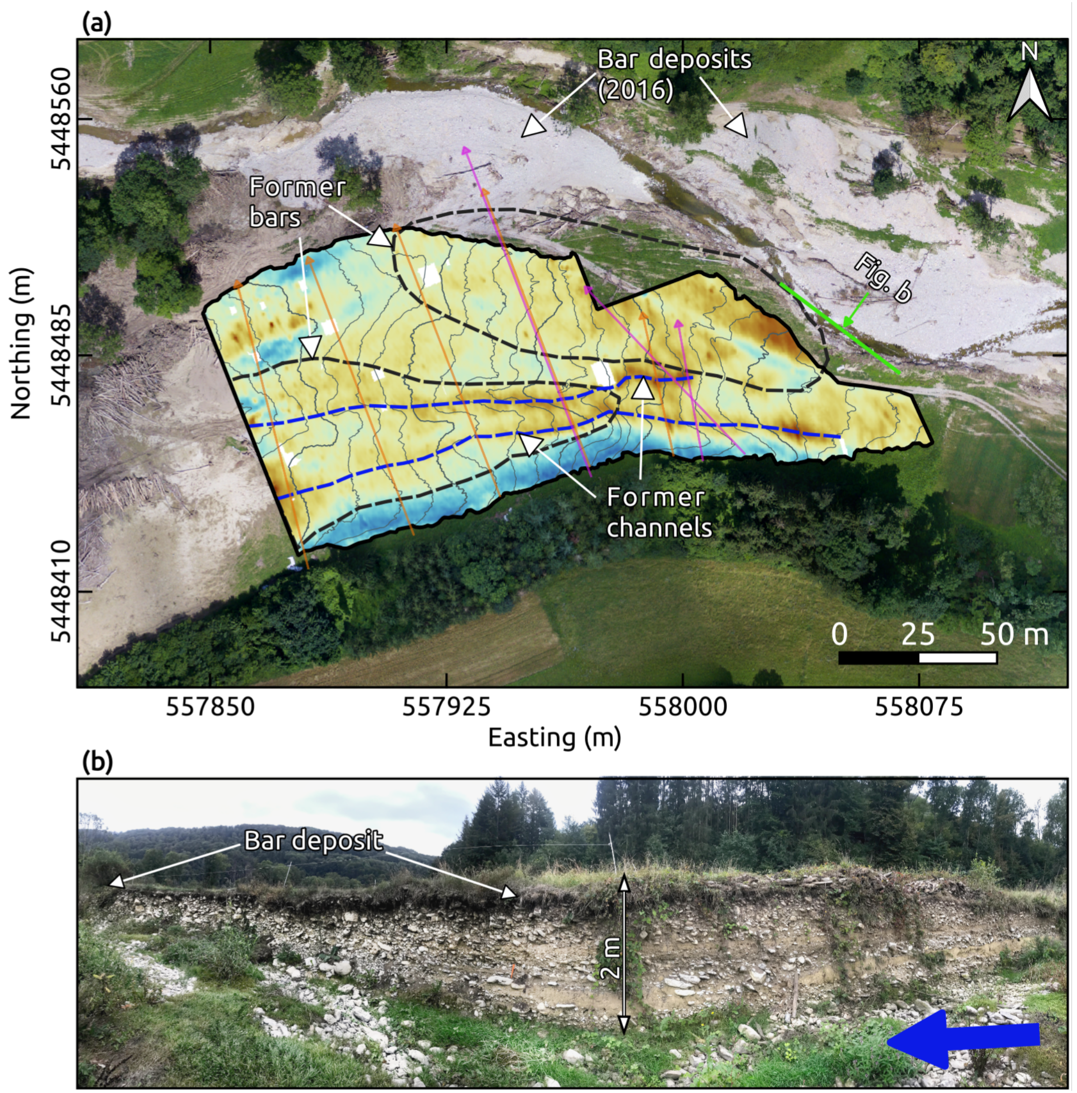



Arboleda-Zapata et.al. (2023), ESPL

# EMI and ERT in practice




Depth slice at 1 m below surface

σ (Sm$^{-1}$)

0.07

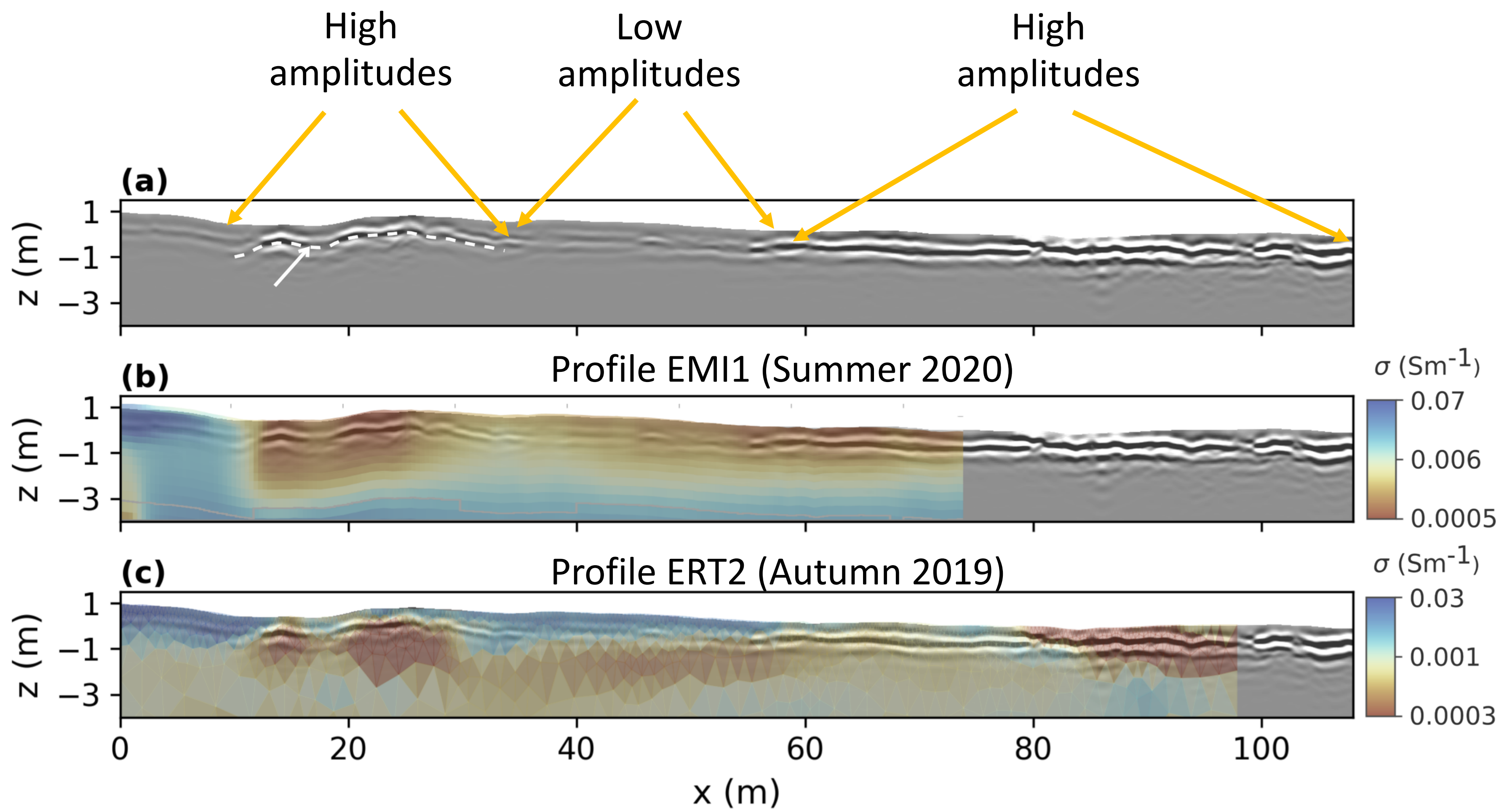
0.006

0.0005

Not all scales have the same color scales. Why?

Arboleda-Zapata et.al. (2023), ESPL

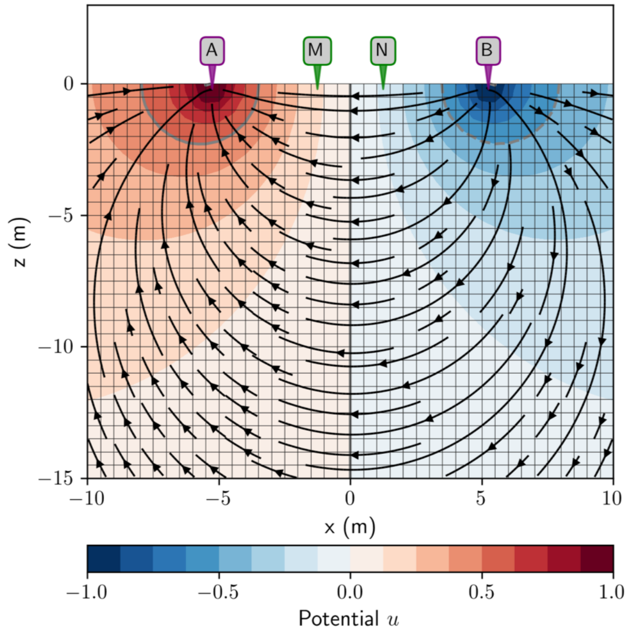
# EMI and ERT in practice + GPR




Note: The color bars are different because the data was collected under different moist conditions, and sensors have different precision (e.g., changes in the temperature in EMI sensors can result in significant conductivity changes; temperature correction is required).

# Part 2

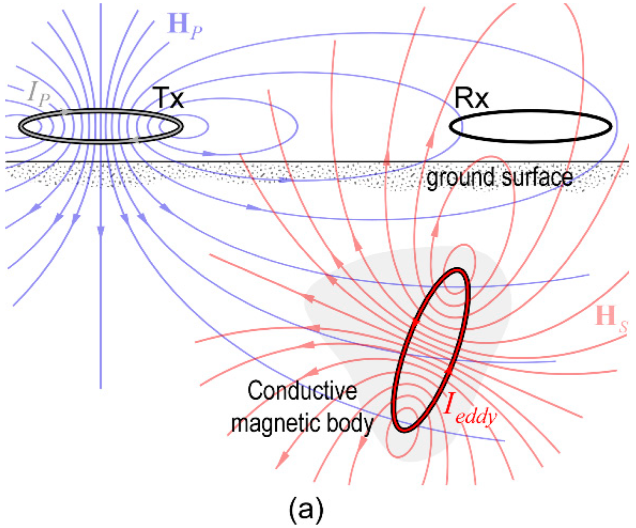
# Electric vs electromagnetic methods




We can obtain the electric resistivity/conductivity using electric and electromagnetic methods.

Electric method

- Advantages
- Disadvantages




Piero Deidda, et al. (2023), Remote Sensing

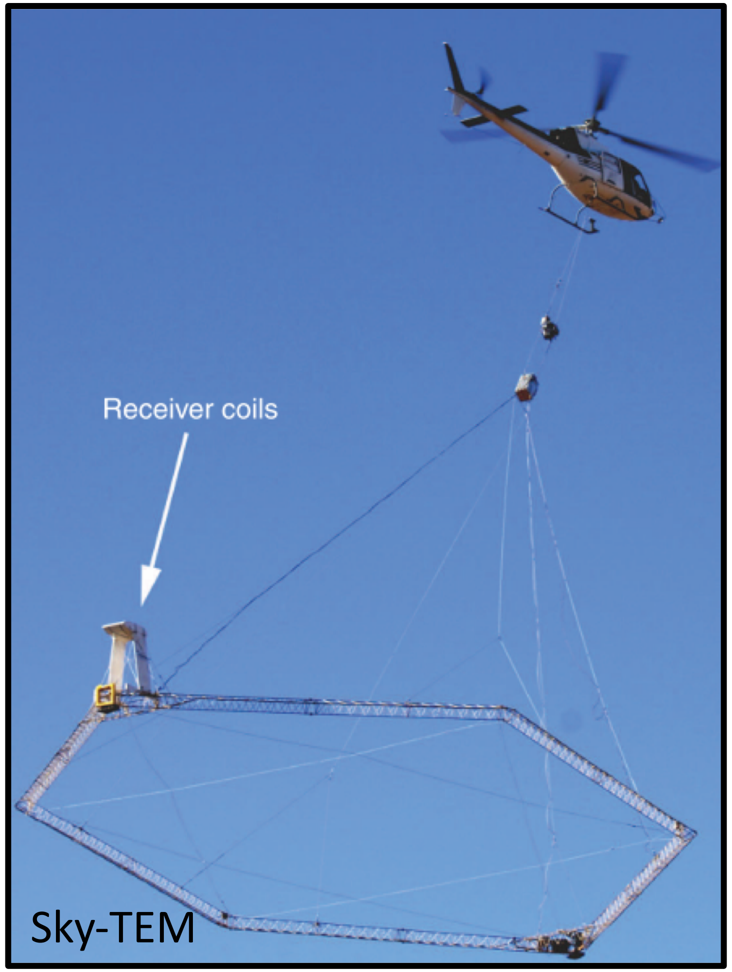
Electromagnetic method

- Advantages
- Disadvantages

# Let’s expand a bit in Time-Domain EM (TDEM)



https://hgg.au.dk/instruments/floatem




Auken et al. (2009), Exploration Geophysics

# TDEM data acquisition

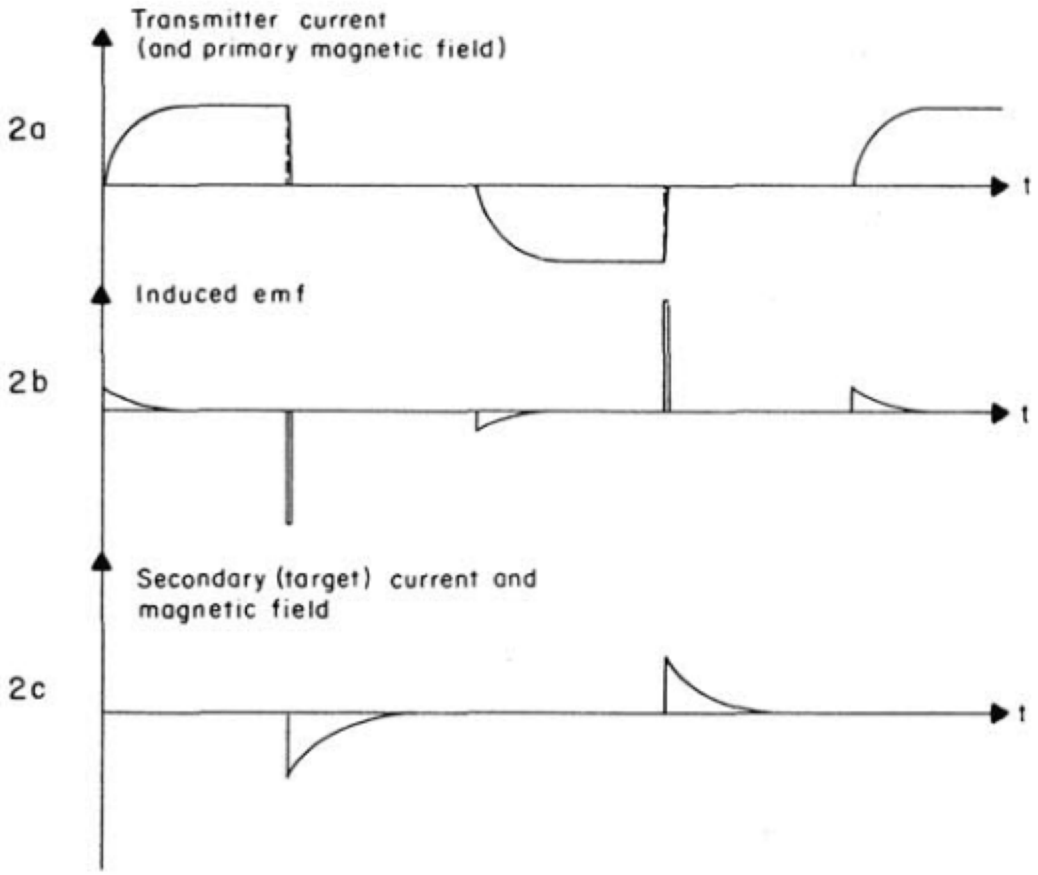
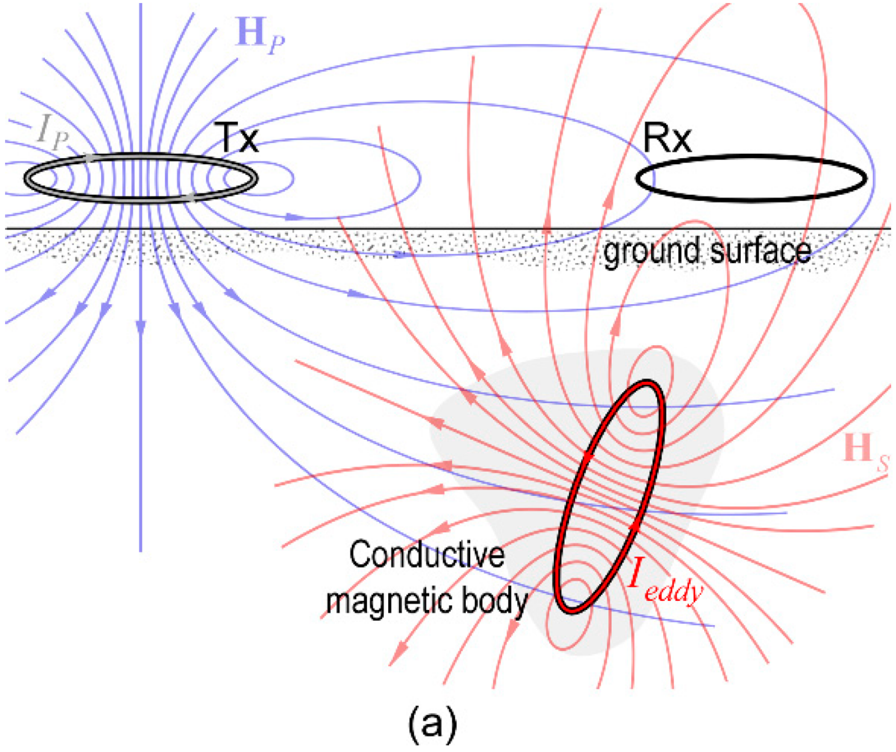


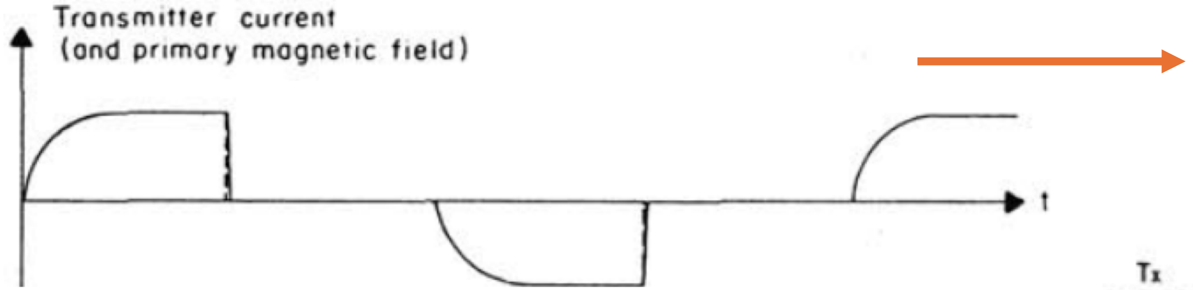

FIGURE 2. System waveforms.

McNeill (1980), Technical Note #7




Piero Deidda, et al. (2023), Remote Sensing

# TDEM data acquisition



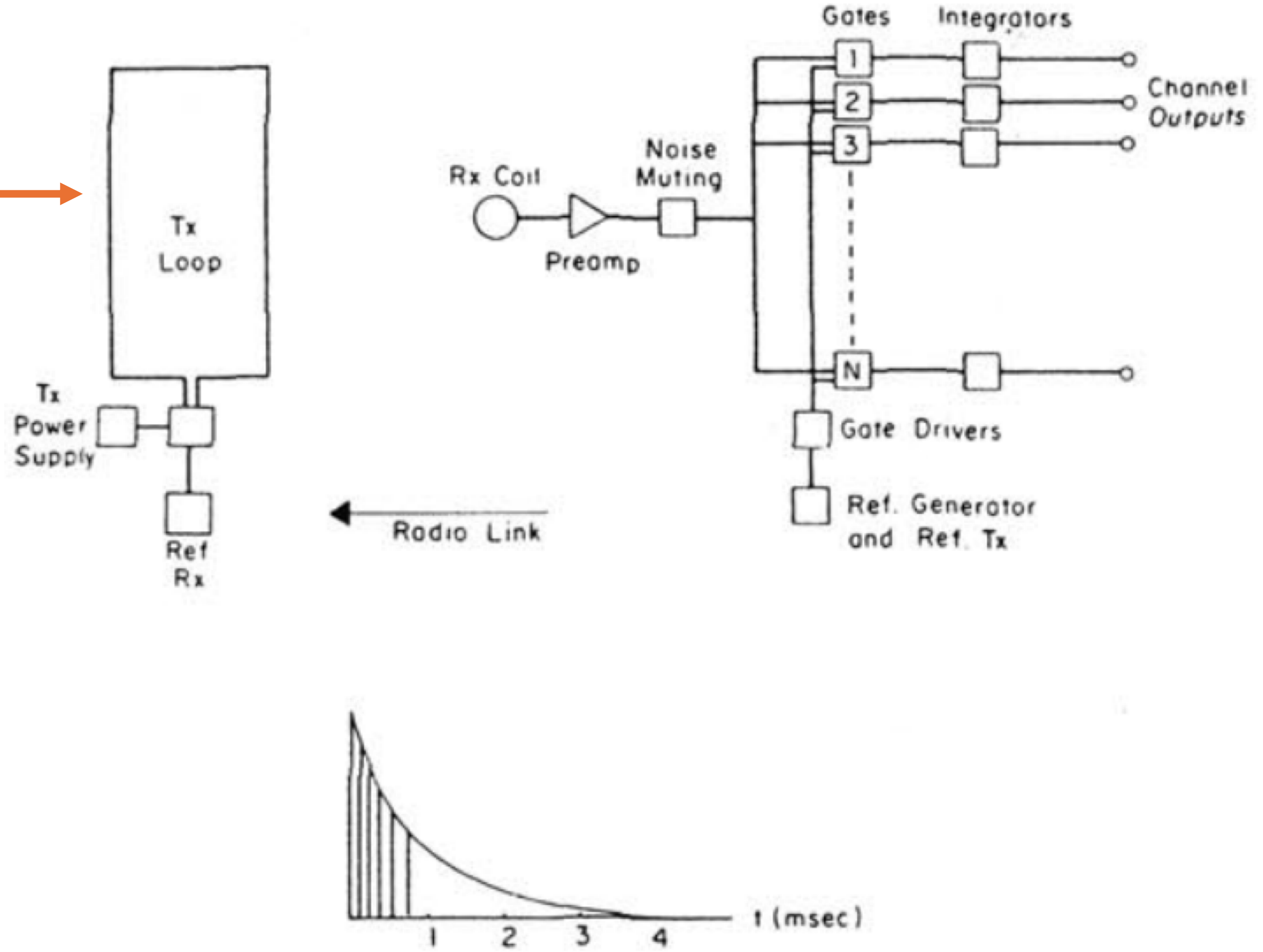
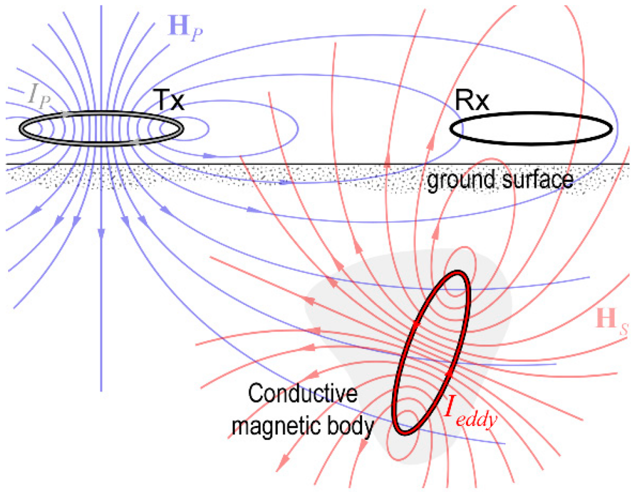




FIGURE 3. Block diagram and typical transient (showing initial gates).



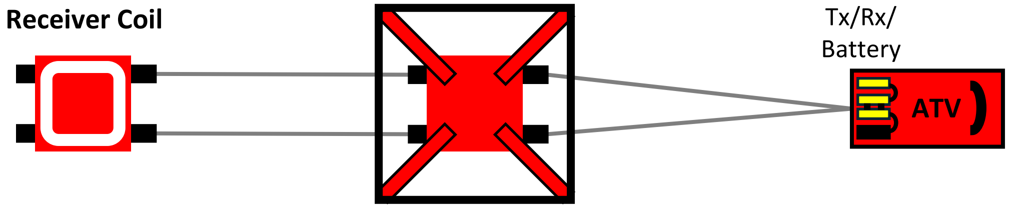

(a)

Piero Deidda, et al. (2023), Remote Sensing

McNeill (1980), Technical Note 7

# TDEM

## The ATV-towed TDEM system (tTEM)





USDA, 2023

Imaging depths of 30 - 70 m

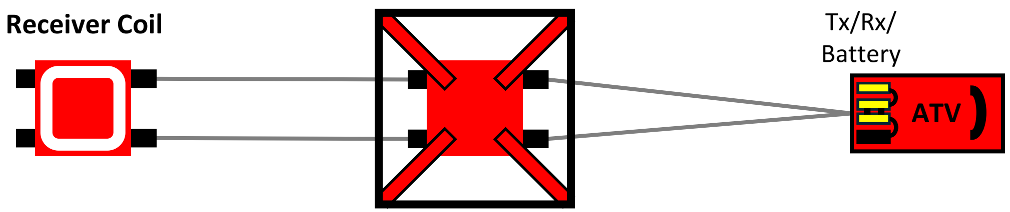
Data can be collected at speeds of 15 – 25 km/s

Dual-transmitter low moment (LM) and high moment (HM)

Resolution:

- Lateral resolution along line (10 m) and between line (25 m - user-dependent)
- Vertical resolution degrades with depth; ~2 m near surface to ~10 m at max. depth

# tTEM





USDA, 2023

**Table 1. System specification with the separate entries for the low-moment (LM) and high-moment (HM) configurations.**

| | Low moment (LM) | High moment (HM) |
|---|---|---|
| Transmitter area (single turn) | 8 $m^2$ | 8 $m^2$ |
| Tx current | ~2.8 A | ~30 A |
| Tx peak moment | ~22.4 $Am^2$ | ~240 $Am^2$ |
| Pulse repetition frequency (50 Hz power line frequency) | 2110 Hz | 660 Hz |
| Number of pulses/time | 422/0.20 s | 264/0.40 s |
| Duty cycle | 42% | 30% |
| Tx on-time | 200 μs | 450 μs |
| Turn-off time | 2.5 μs | 4.0 μs |
| Gate time interval (from beginning of turn-off) | 4–33 μs | 10–900 μs |
| Number of gates | 15 | 23 |

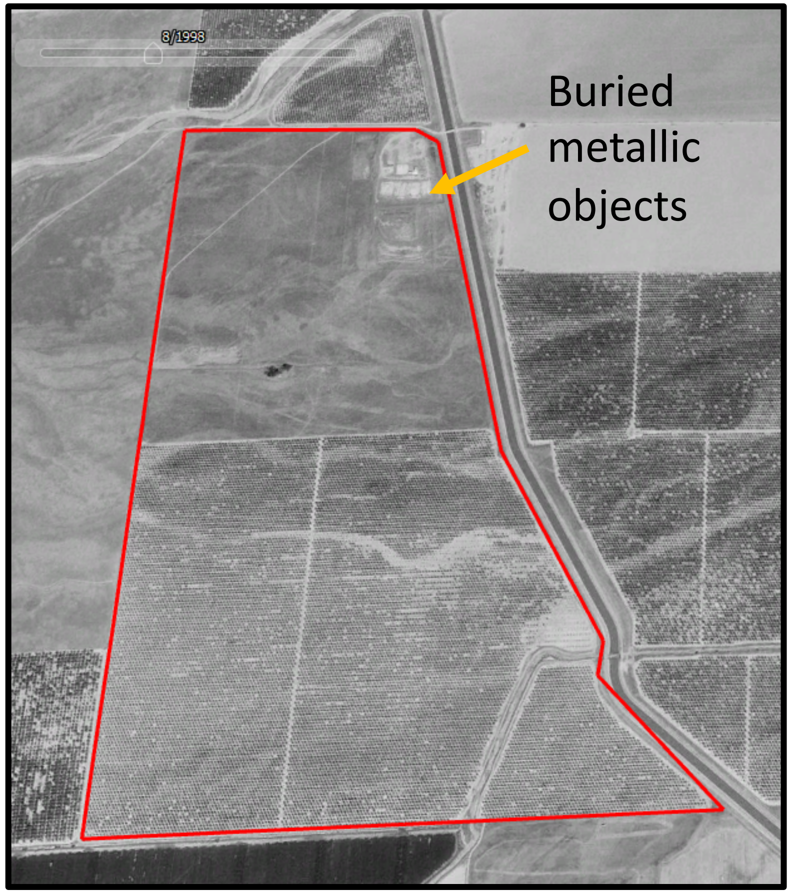
Auken et al. (2019), Geophysics

# Sources of error

- Geometric (e.g., Tx vs Rx, Topography, turning the ATV …)
- Geomagnetic signals
- Induced polarization
- Power lines
- Radio signals
- Electric fences
- Metallic objects (if these ones are not the target)
- System temperature
- …

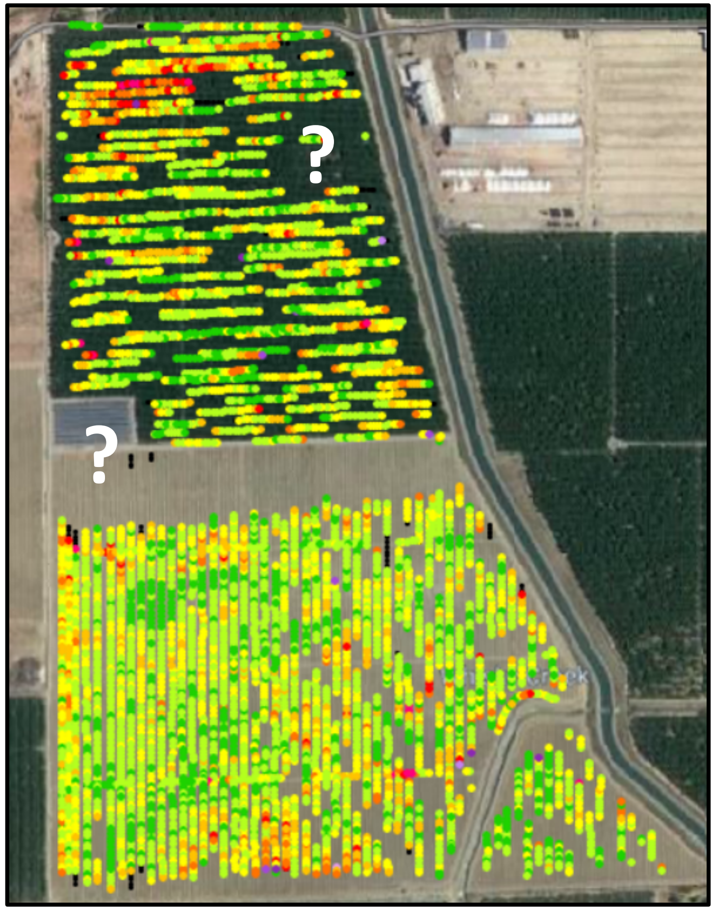
# Example of sources of error

Study area




Google Earth, 1998

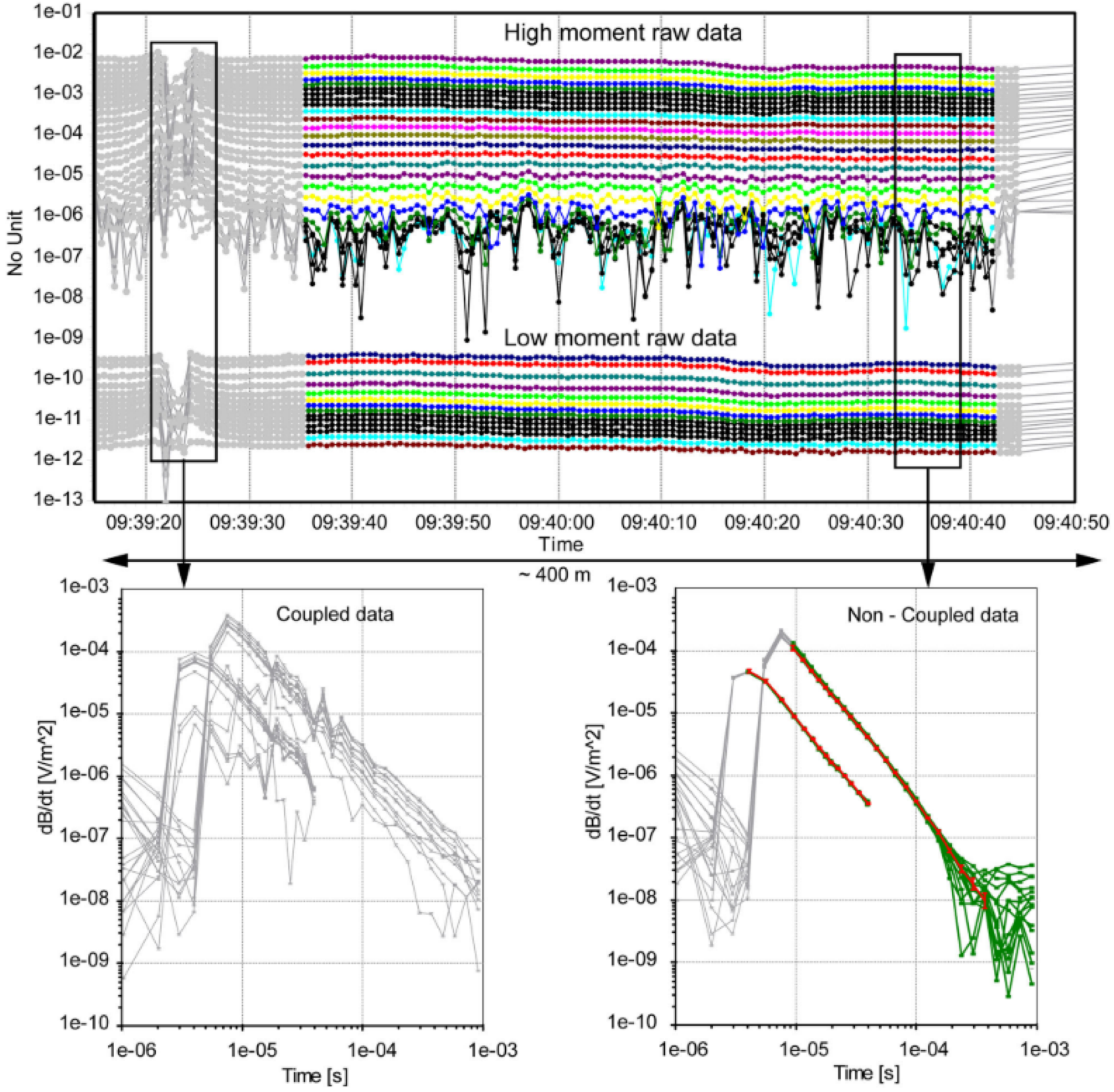
Data misfit values. Green and red means good and bad data misfits




USDA, 2023

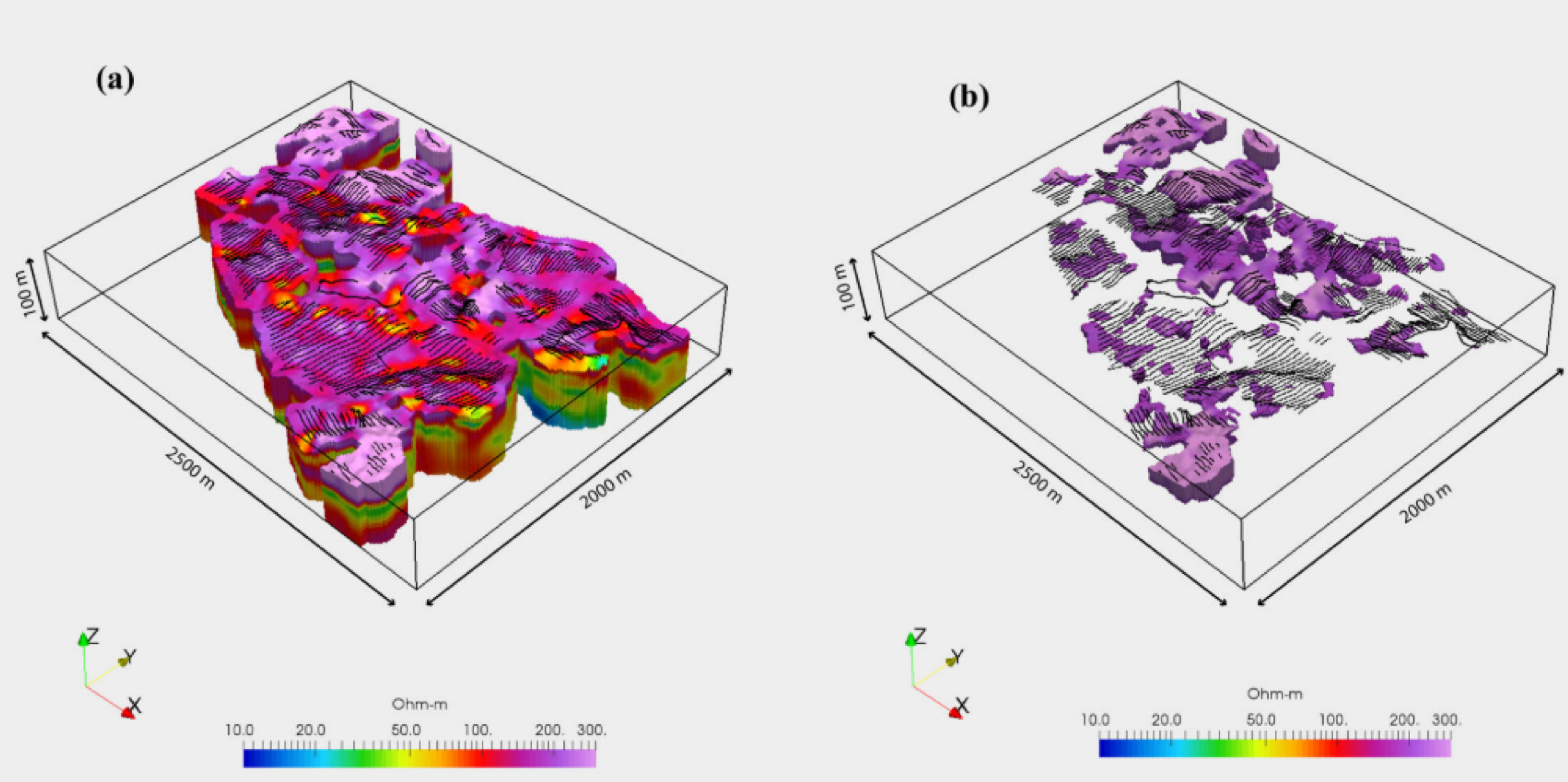
# tTEM
# Data processing

- Remove coupled data (man-made infrastructure, e.g., power lines)
- End-of-line turns are removed
- Data is averaged every 2-3 seconds (depending on the velocity system is moved with a vehicle).




Maurya et al. (2020), NSG

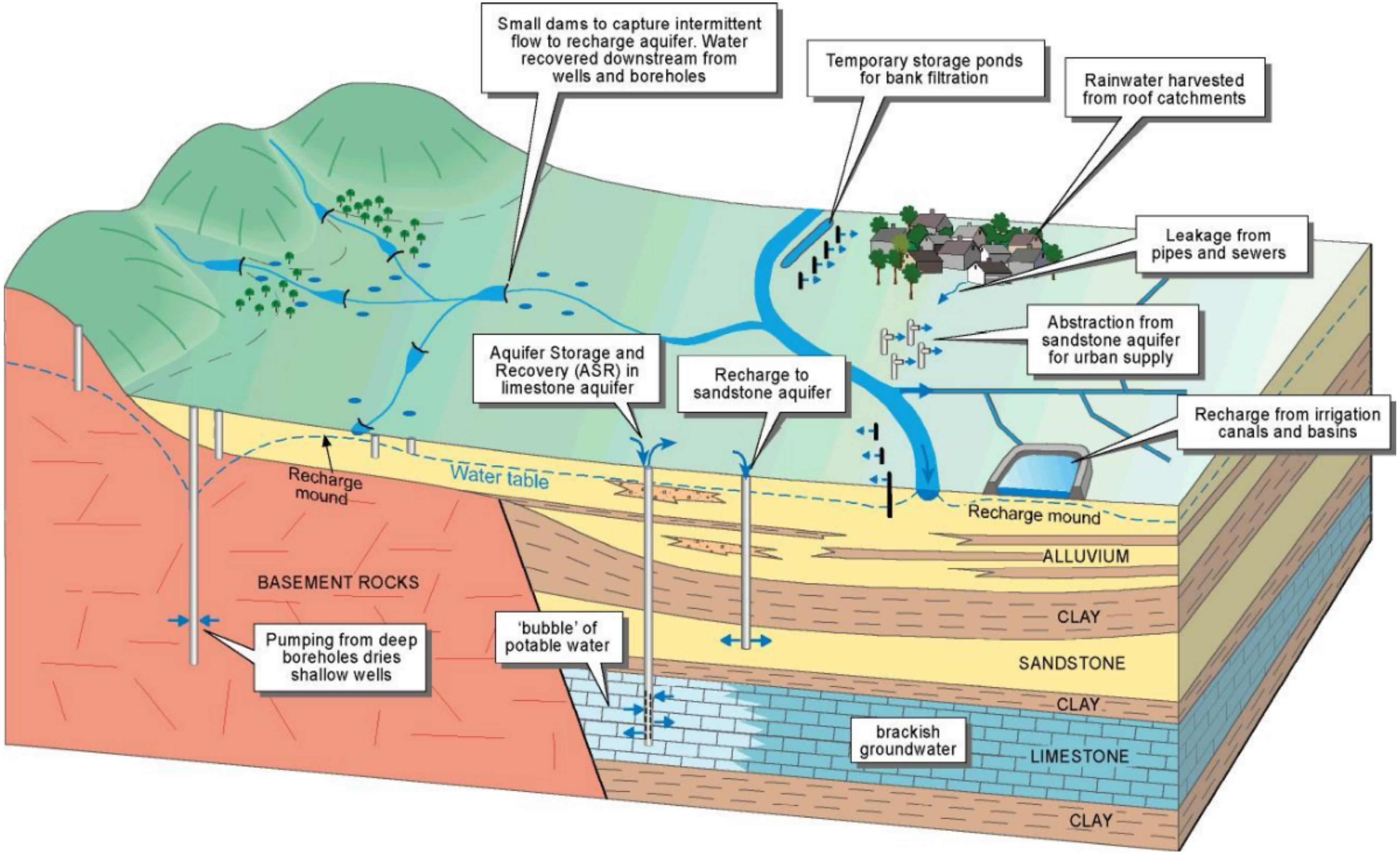
# tTEM - Data Inversion




Maurya et al. (2020), NSG

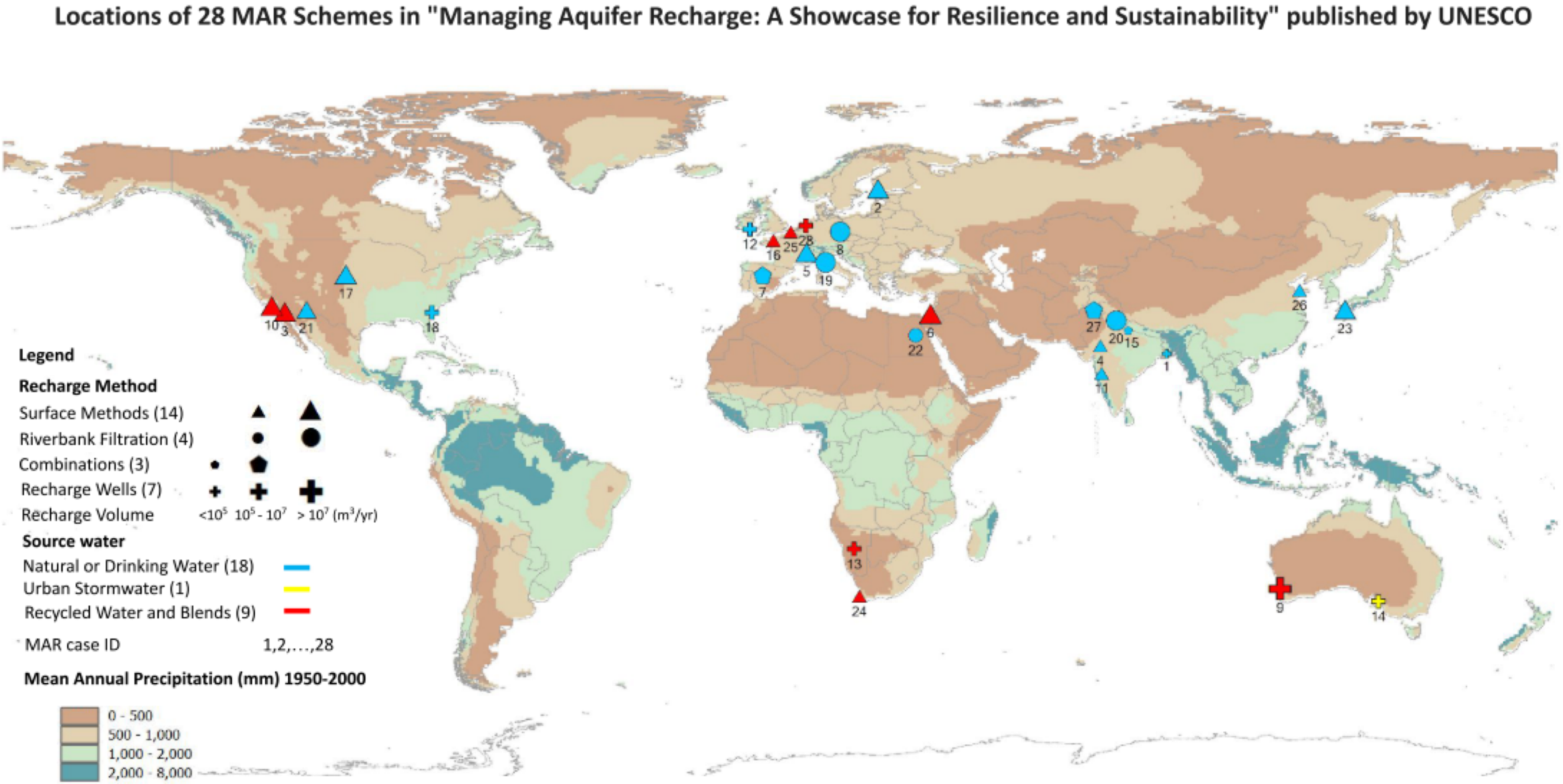
# Case study: Defining a suitable managed aquifer recharge strategy based on tTEM data

# Manage aquifer recharge (MAR)




Gale et al. (2002)

# Case study: Defining a suitable managed



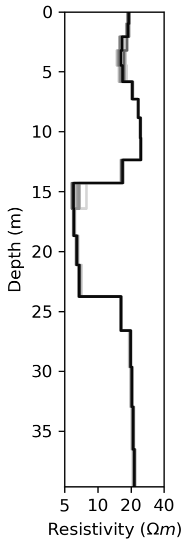

Zheng et al. (2021)

# Data Acquisition: tTEM

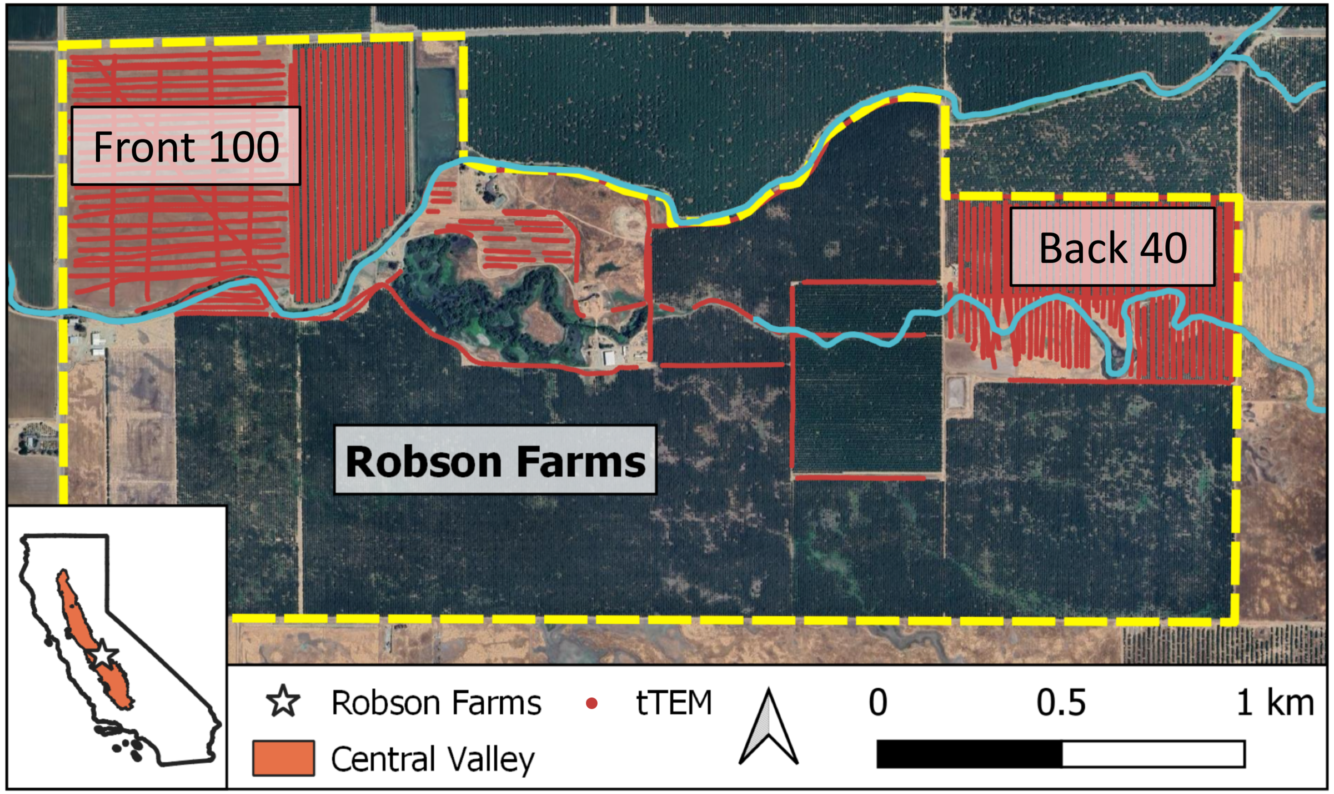
tTEM data acquired over two days in June 2023

Target Front 100 and Back 40

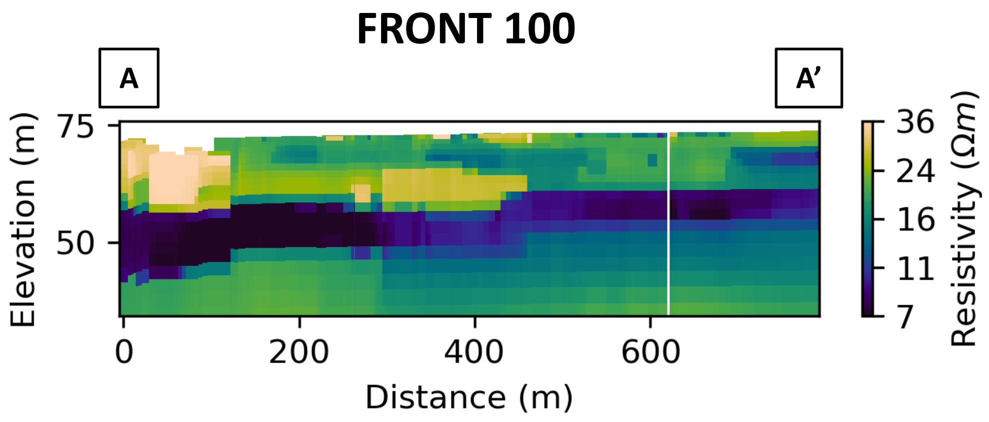
Dirt roads and adjacent fields surveyed

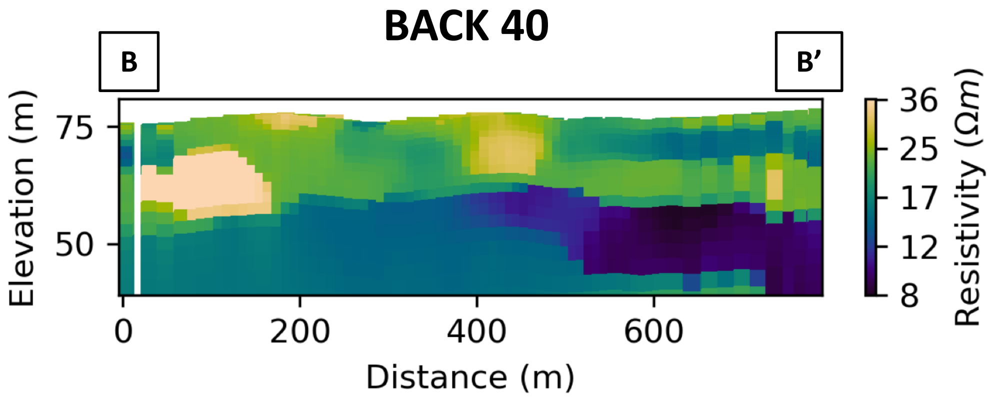


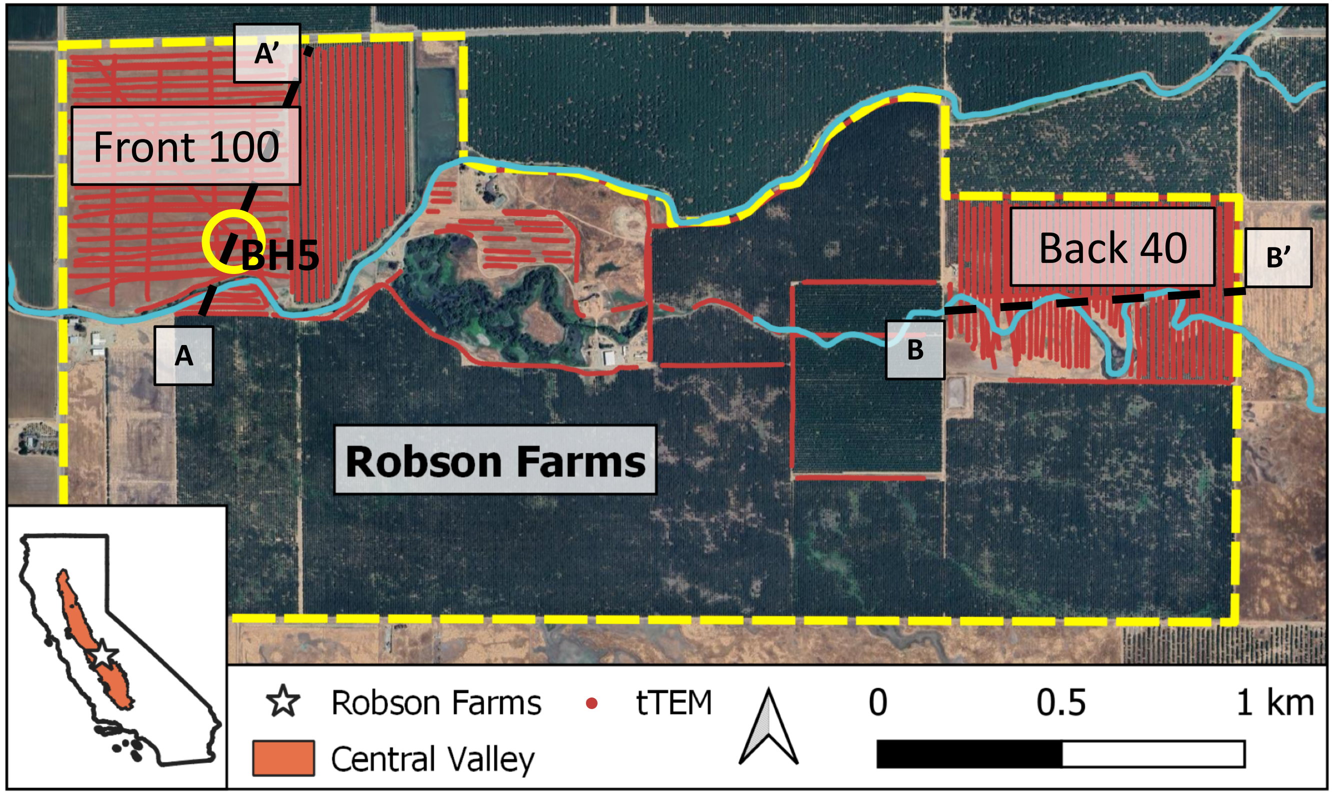

Example tTEM sounding



# tTEM Cross-Sections



# Estimated Sediment Type at Log 5

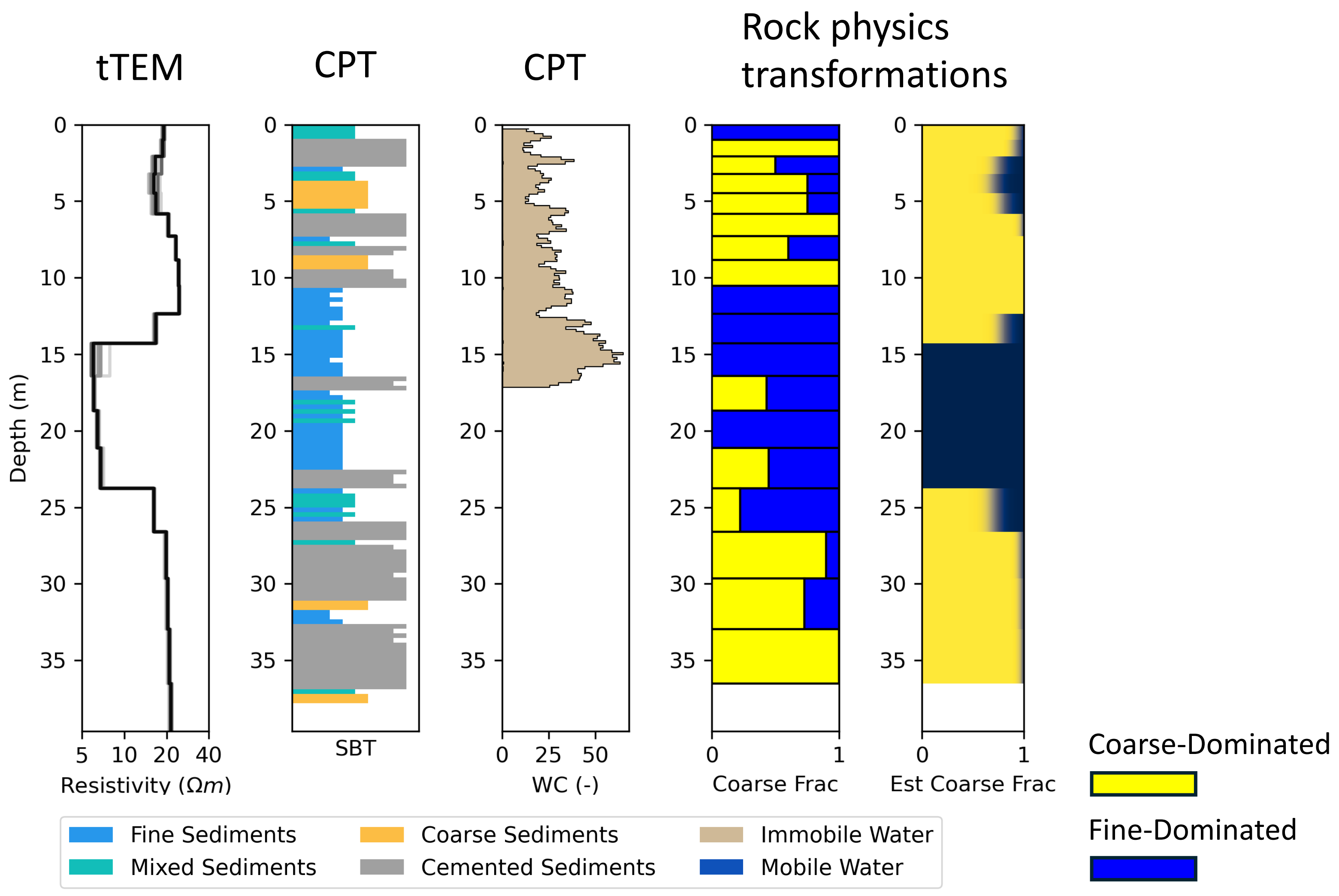
Example: Log 05

Panels show (left to right)

- tTEM resistivity profile
- CPT soil behavior type log
- bNMR water content log
- Re-classified CPT log
- tTEM-estimated sediment type

tTEM images large-scale features

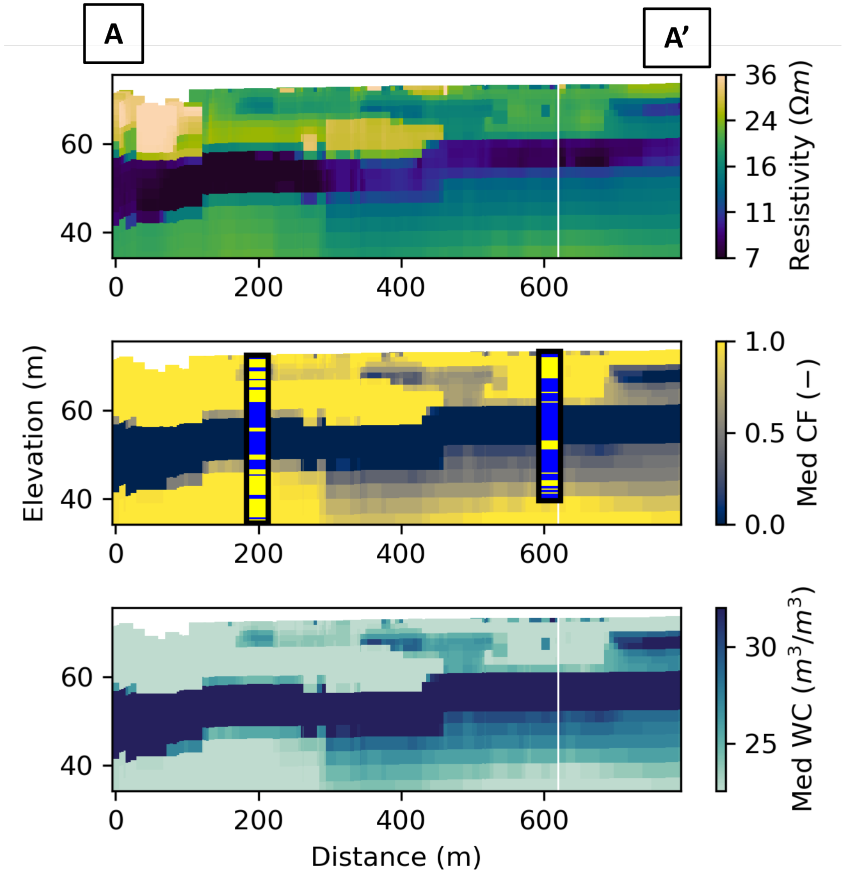
- Smaller features not visible

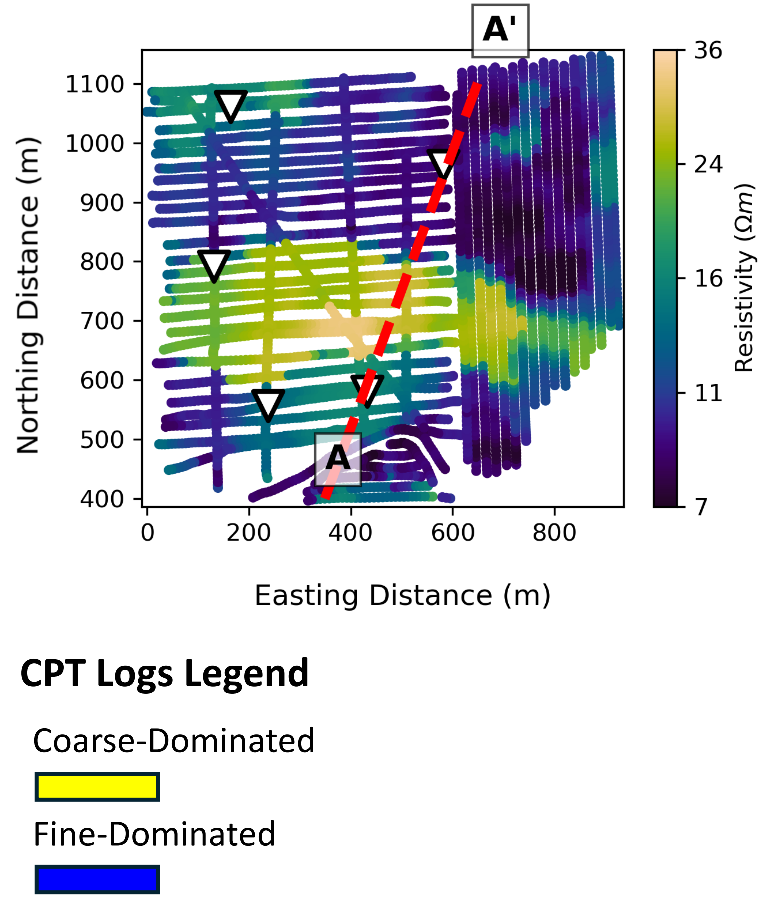


# Hydrogeological Models: Front 100

Panels show (top to bottom)

- tTEM resistivity cross-section
- tTEM-estimated sediment type (median coarse fraction)
  - Categorized CPT logs shown
- tTEM-extrapolated water content (median water content)




Thick, low-resistivity layer at ~50-60 m elevation

- Low estimated coarse fraction (i.e., fine-rich)
- High estimated water content

# Summary

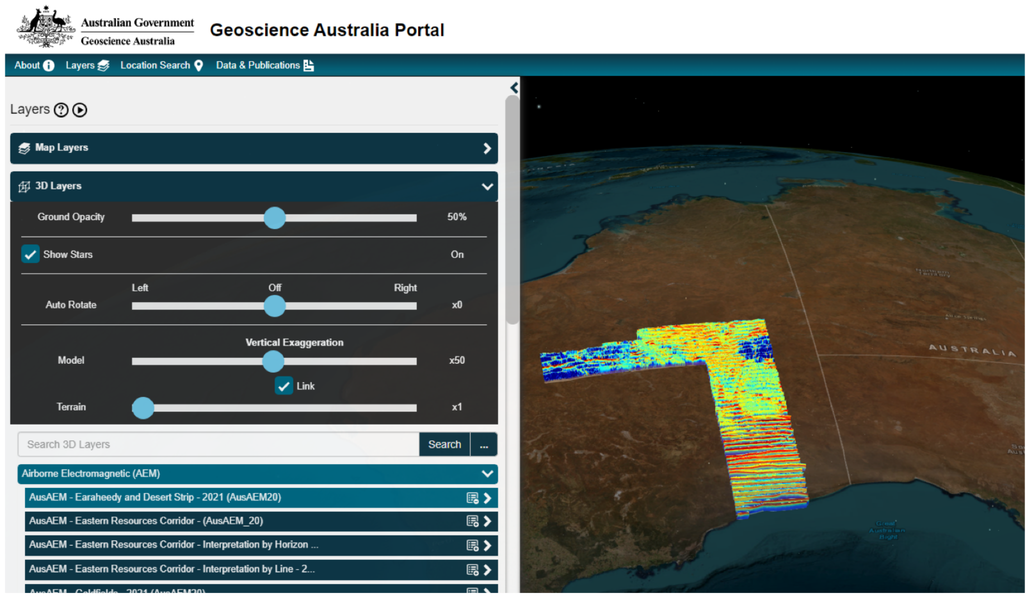
- Resistivity can be imaged by using resistivity (ohm law), electromagnetic induction, and the magnetotelluric method.
- For EMI, we are interested in a function that links the primary with the secondary magnetic field.
- For TDEM, we are interested in the decay with time of the voltage generated by the secondary magnetic field.
- Rock physics transformations might be required to infer other material properties such as grain size distribution and water content.
- What about applications for monitoring changes in resistivity?

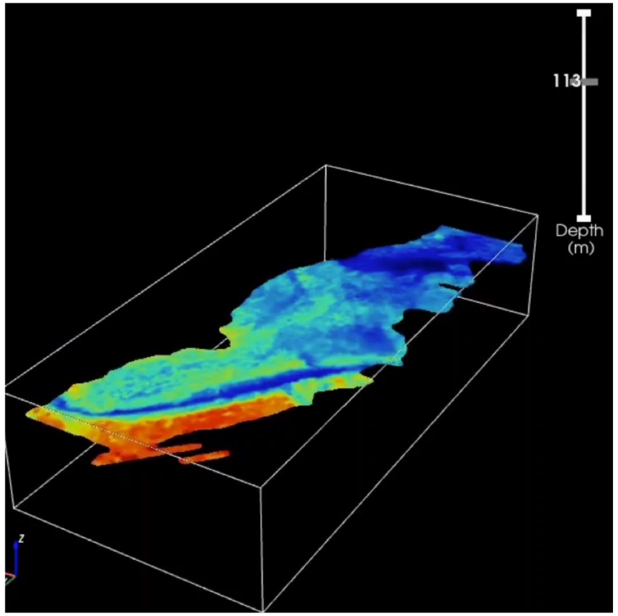
# Links to complementary material

- https://hgg.au.dk/instruments/ttem
- https://geonics.com/html/technicalnotes.html
- https://em.geosci.xyz/index.html

# Open source data sets

- https://usgs.maps.arcgis.com/apps/Cascade/index.html?appid=dd89868e7d524197a718d216732c5d04&classicEmbedMode
- https://data.cnra.ca.gov/dataset/aem
- https://portal.ga.gov.au/3d



# Open source software

Simpeg

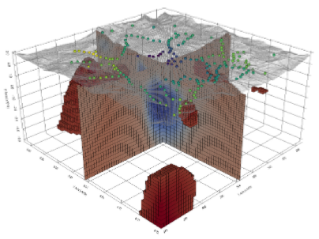
## Simulation and Parameter Estimation in Geophysics

An open source python package for simulation and gradient based parameter estimation in geophysical applications.

### Geophysical Methods

Contribute to a growing community of geoscientists building an open foundation for geophysics. SimPEG provides a collection of geophysical simulation and inversion tools that are built in a consistent framework.

- Gravity
- Magnetics
- Direct current resistivity
- Induced polarization
- Electromagnetics
  - Time domain
  - Frequency domain
  - Natural source (e.g. Magnetotellurics)
  - Viscous remanent magnetization
- Richards Equation



pyGIMLi

*Geophysical Inversion & Modelling Library*

## pygimli.physics

Module containing submodules for various geophysical methods.

**Module overview**

| | |
|---|---|
| `em` | Frequency-domain (FD) or time-domain (TD) semi-analytical 1D solutions |
| `ert` | Electrical Resistivity Tomography (ERT) |
| `gravimetry` | Solve gravimetric and magneto static problems in 2D and 3D analytically |
| `petro` | Various petrophysical models |
| `seismics` | Full wave form seismics utilities and simulations |
| `SIP` | Spectral induced polarization (SIP) measurements and fittings. |
| `sNMR` | Surface nuclear magnetic resonance (NMR) data inversion |
| `traveltime` | Refraction seismics or first arrival traveltime calculations. |
| `petro` | Various petrophysical models |
| `ves` | Direct current electromagnetics |

# Acknowledgment

- Dr. Gordon Osterman from USDA in Davis, California for providing slides material for the managed aquifer recharge example.